TREATMENT OF REFINERY WASTEWATER USING CROSSFLOW MEMBRANE BIOREACTOR (CF-MBR)

BY

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Dedicated

To My Parents

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ABSTRACT

Name: Muhammad Muhitur Rahman

Title: Treatment of Refinery Wastewater Using Crossflow Membrane Bioreactor (CF-MBR)

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Membrane Bioreactors have gained a considerable attention in the recent years for treating industrial wastes with an extensive advancement in the membrane technology. A Crossflow Membrane Bioreactor (CF-MBR) is one of the modifications to the conventional activated sludge process. It is the combination of a membrane module and an aeration tank containing the Mixed Liquor Suspended Solids (MLSS) that gives frequent benefits over the conventional wastewater treatment process. However, the biokinetics and performance of different operating parameters associated with this process are required to better design this type of treatment plant and to meet the effluent standards. The major objective of this study is to investigate the kinetics and the performance of crossflow membrane bioreactor for treating oily wastewater at two different MLSS concentrations (5000 and 3000 mg/l). The performance was measured based on the hydraulic efficiency (variation of flux, hydraulic retention time and transmembrane pressure) as well as the COD removal efficiency of the system. Several organic (BOD, TOC, oil & grease, phenol and ammonia) and microbial (heterotrophic plate count) parameters to evaluate the permeate water quality were measured throughout the study period. The effect of HRT on the system performance and the cleaning mechanism of the ceramic membrane were also investigated.

During the biokinetic study period at concentrations of MLSS 5000 mg/l and 3000 mg/l, high removal efficiency (93-94%) was observed and the removal efficiency was not improved with increasing the MLSS concentration (from 3000 mg/l to 5000 mg/l). At MLSS 5000 mg/l, the kinetic coefficients were: $Y = 0.276$ mg/mg, $k_d = 0.07$ day^{-1}, $\mu_m = 0.653$ day^{-1} and $Ks = 396.62$ mg COD/l, which were 0.222 mg/mg, 0.09 day^{-1}, 1.20 day^{-1} and 659.45 mg COD/l for MLSS concentration of 3000 mg/l, respectively. The simulation study in predicting the effluent COD at various SRTs, showed good agreement between model predictions and experimental data. The model can be used to simulate and investigate different operational strategies. Flux increased with the increasing crossflow velocity and thus can be expressed by the power law relationship ($J = kV^n$). The constants k and n were found to be dependent on MLSS concentrations. In the study of effect of HRT on system performance, the maximum COD removal efficiency (95%) occurred at an optimal operating condition of HRT 34 hr, SRT 67 day and CFV of 2.21 m/s at MLSS 5000 mg/l. The same removal efficiency was occurred at MLSS 3000 mg/l in combination of operating parameters of HRT 33 hr, SRT 31 day and CFV of 2.25 m/s. COD Removal efficiency was found to be independent of HRT at different MLSS concentration in this study. The standard plate count showed one log reduction in permeate colony forming units during the experimental period which is not satisfactory. In removing the fouling of the membrane, combination of chemical washing with an acidic detergent followed by the backwash was regarded as the best solution for fouling control in sense of cleaning time and recovered flux.

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الملخّص

الاسم **محمد مهاتير رحمن**

عنوان الرسالة **معالجة مخلفات تكرير البترول بإستخدام معالج حيوي غشائي معترض للجريان**

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مع تطور تقنيات صناعة الاغشية النسيجية إكتسب إستخدام الغشاء المعالج الحيوي اهتمام كبير في السنوات الآخيرة في مجال معالجة النفايات الصناعية. الغشاء المعالج الحيوي معترض الجريان هو احد النماذج المعدله لعملية تنشيط الحماءة. يشتمل المعالج الحيوي على غشاء وحوض تهوية يحتوي على خليط المواد العالقة **(MLSS)** مما يجعله افضل من نظام المعالجة التقليدي، كما ان نظام التدفق وطريقة اداء هذا النظام العوامل التشغلية المصاحبة لعملية المعالجة تعتبر مهمة لاغراض التصميم ومطابقة المواصفات. الهدف الرئيس من هذه الدراسة هو تتبع حركة واداء المعالج الحيوي الغشائي المعترض للجريان عند إستخدامه في معالجة مخلفات تكرير البترول في وجود نسب مختلفة لتركيز العوالق (5000 و3000 ملجرام/لتر). لقد تم قياس الأداء بناءً على الكفاءة الهيدروليكية (تغير الدفق، زمن الحجز والضغط عبر الغشاء) بالاضافة لكفاءة إزالة الاكسجين الكيميائي المطلوب **(COD)**. تم قياس عدد من المكونات العضوية (الاكسجين الحيوي المطلوب **BOD**، الكربون العضوي **TOC**، الزيوت والشحوم، الفينول والنشادر) والبكتريا الحيوية لتقييم جودة المياه المعالجة خلال فترة الدراسة. ايضاً تمت دراسة اثر زمن البقاء الهيدروليكي وطريقة نظافة الغشاء على أداء نظام المعالجة.

وجدت نسبة إزالة عالية (93-94%) عند دراسة الحركة الاحياء في نظام المعالجة عند درجات تركيز عوالق 5000 ملجرا/لتر و3000ملجرام/لتر ولم يلاحظ اي تحسن عندي زيادة تركيز المواد العالقة من 3000ملجرام/لتر إلى 5000 ملجرام/لتر. عند تركيز 5000 ملجرام/لتر كانت معاملات الحركة: $(Y = 0.276\ mg/mg,\ k_d = 0.07\ day^{-1},\ \mu_m = 0.653\ day^{-1}\ and\ Ks = 396.62\ mg)$ بينما كان تركيز الاكسجين الكيميائي المطلوب 0.222 ملجرام/ملجرام 0.90 /يوم، 1.2/يوم و 659.45 ملجرام لتركيز 3000 ملجرام/لتر على التوالي. اظهر نظام المحاكاة الذي أجري على ازمنة مختلفة لحجز المواد الصلبة ان هناك توافق كبير بين نتائج نموذج المحاكاة والنتائج المخبرية. يمكن استخدام نموذج المحاكاة لتمثيل استراتيجيات وعمليات تشغيل مختلفة. يتناسب معدل الدفق طرديا مع السرعة خلال الغشاء ويمكن تمثيل ذلك بالعلاقة $J=kV^n$ حيث وجد ان قيم k و n تعتمد على تركيز المواد العالقة. عند دراسة اثر زمن الحجز الهيدروليكي على اداء نظام المعالجة وجد ان نسبة إزالة الاكسجين الكيميائي تصل إلى 95% عند نظام تشغيل مثالي بزمن حجز هيدروليكي 34 ساعة وزمن حجز المواد الصلبة 67 يوم وسرعة عبور الغشاء 2.21 متر/ثانية وتركيز مواد صلبة يساوي 5000 ملجرام/اللتر. وجد ان نفس نسبة الازالة السابقة يمكن ان تحصل عند تركيز 3000 ملجرام/لتر عند زمن حجز هيدروليكي 33 ساعة وزمن حجز للمواد الصلبة 31 يوم وسرعة عبور الغشاء 2.25 متر/ثانية. كما وجد ان نسبة ازالة الاكسجين الكيميائي لا تعتمد على زمن الحجز الهيدروليكي. اظهرت صفيحة العد القياسية ان هناك نقصان بمقدار وحدة في نسبة البكتريا خلال فترة المعالجة وهي غير كافية. تم الاخذ في الاعتبار عند تنظيف الغشاء استخدام حامض مطهر مع ضخ خلفي للمياه وقد وجد انه انجح طرق التنظيف من حيث زمن التنظيف وكفاءته.

درجة الماجستير في العلوم
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CHAPTER 1

INTRODUCTION

The occurrence of oil-containing wastewater and the corresponding contamination of water sources by oil began with the production and utilization of petroleum and its products. Before the introduction of the wastewater treatment and reuse, it was a common practice to discharge the wastes into rivers or bare surface. However, the strict regulations, increased hauling costs, and environmental concerns made oily wastewater treatment a prominent issue for most industries.

The type and concentration of pollutants in a given refinery's effluent depends on the chemical make-up of the crude oil and the processes used to make the final products. Refineries use large amounts of water in the refining process and as a cooling agent. This water picks up waste oil and impurities from the refining process. Some impurities are in the crude oil itself such as heavy metals, sulfide, and phenols, while others are created during the refining process such as cyanide, dioxins, and furans. All of these chemicals can be toxic to aquatic life at very low concentrations. The major problem of oily wastewater is associated with its suitable disposal. The refinery wastewater has been marked as one of the key environmental pollutant with great effect on the biodiversity. The reclamation and reuse of such oily wastewaters is needed especially in the oil producing arid regions because of water scarcity. Though there are several

methods for treating the oily wastewater, but still investigation for improving the plant performance in terms of better effluent quality, cost effectiveness, and to cope with the current development of technology, the search for alternative treatment methods is required.

Activated sludge process is one of the alternatives for treating industrial wastes. In this system the final settling tank is a vital part, which combines two functions i.e., clarification and thickening. An improper functioning would result in solids being carried over with the final effluent. Membrane separation technology is agreed to be an attractive alternative for the solid/liquid separation in the aeration tank because of space, cost, and effluent water quality and maintenance concerns. The use of a membrane for solid separation instead of a gravity clarifier eliminates many of the solid separation problems associated with the conventional activated sludge process.

The configuration of membrane along with activated sludge commonly known as Membrane Bioreactor (MBR) is of two types. The first one is membrane bioreactors with internal submerged membrane filtration (SM-MBR) where the membrane filtration is carried out directly in the activated sludge tank. Another is membrane bioreactor with external membrane filtration (CF-MBR) where the membrane filtration is carried out outside the activated sludge tank. The concentrate, that is the retained activated sludge, is returned to the activated sludge tank. Crossflow membrane filtration (CF-MBR) appears to offer an attractive alternative for solid/liquid separation since it is possible to retain up to 100% of the biomass and thus run the aeration tank at any desired level of mixed liquor suspended solids. It has the added advantage of consistently producing an effluent almost free from suspended solids with less

operational problems. Moreover, the flocculating characteristics of the activated sludge are not relevant to the quality of effluent (El-kebir, 1991).

This research was initiated in order to study the interaction between the biological and filtration unit of CF-MBR. For this purpose the biochemical kinetics of the CF-MBR system and its dependency on the Mixed Liquor Suspended Solid (MLSS) concentrations was investigated. The performance of the CF-MBR system at different MLSS concentrations was also assessed. The performance was measured based on the hydraulic efficiency (variation of Flux, Hydraulic Retention Time and Transmembrane pressure) as well as the COD removal efficiency of the system. Several organic (BOD, TOC, Oil & grease, Phenol and Ammonia) and microbial (Heterotrophic Plate Count) parameters to evaluate the permeate water quality were measured throughout the study period. The effect of HRT on the system performance at different MLSS was also investigated. The fouling of the membranes comes very synonymously with the application of MBR. Several methods were proposed to reduce the membrane fouling and prolong the lifespan of the membrane.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Membrane bioreactor, a modification of the conventional activated sludge process, plays an important role in the treatment of industrial wastewater. In conventional final clarifiers, only the fraction of the activated sludge that forms flocs and settles can be retained, while in MBR, all parts of the activated sludge that are larger than the pore size of the membrane are retained. As a result, the separation of the activated sludge from cleaned wastewater is independent of the sedimentation qualities of the activated sludge and is only dependent on the membrane (Gunder, 2001). Discussion is needed on activated sludge process (ASP) and membrane filtration, the processes that constitute the membrane bioreactor system, to understand the different aspects of MBR. In the following, literature related to ASP, crossflow filtration, CF-MBR and the factors that affect the CF-MBR are reviewed to give a general overview of different system in comparison to CF-MBR system in the treatment of industrial wastewater.

2.2 CHARACTERISTICS, SOURCES AND TREATMENT ALTERNATIVES FOR OILY WASTEWATER

First of all physicochemical composition of oils in wastewater must be examined, for its appropriate treatment. A primary component of oil contaminants are natural crude

and its derivatives. Petroleum is an oily liquid, usually flowing easily and more rarely of low mobility. It typically contains 82-87% carbon, 11-15% hydrogen, 0.1-7.0% sulfur, 0.6% nitrogen, 1.5% oxygen, and also trace quantities of iron, calcium, potassium, sodium, vanadium, bromine, iodine, arsenic, and other elements (Pushkarev et al., 1983).

The combined refinery wastes, however, may contain crude oil, and various fractions thereof, dissolved or suspended minerals, organic compounds discharged in liquors, and sludges from the various stages of processing. The oil may appear in wastewaters as free oil, emulsified oil, and as a coating or suspended matter, typically not in proportions greater than 100 ppm. Petroleum refineries use relatively large volumes of water, especially for the cooling systems. The quantity of wastewater generated and their characteristics depend on the process configuration. Refinery wastewater contain: biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels of approximately 150–250 and 300–600 mg/l, respectively, phenol levels of 20–200 mg/l; oil levels of 100–300 mg/l in desalter water and up to 5,000 mg/l in tank bottoms, benzene levels of 1–100 mg/l, benzo(a)pyrene levels of less than 1 to 100 mg/l, heavy metals levels of 0.1–100 mg/l for chrome and 0.2–10 mg/l for lead, and other pollutants (World Bank Group, 1998).

Wastes from the oil refineries include free and emulsified oil from leaks, spills, tank draw-off, and other sources; waste caustic, caustic sludge, and alkaline water; acid sludges and acid waters; emulsion incident to chemical treatment; condensates water from distillate separators; tank-bottom sludges; coke from equipment tubes, towers, and other locations; acid gases; waste catalyst and filtering clays; special chemicals from

by-product chemical manufacture; and cooling waters. Oils from leaks and spills can amount to as much as 3 per cent of the total crude oil treated.

Refinery wastewaters often require a combination of treatment methods to remove oil and contaminants before discharge. Separation of different streams, such as storm water, cooling water, process water, and sanitary water is essential for minimizing treatment requirements. A typical system may include sour water striping, gravity separation of oil and water, dissolved air floatation, biological treatment, and clarification. A final polishing step using filtration, activated carbon, or chemical treatment may also be required. Thorough knowledge of the oils physicochemical properties and a better understanding of oil-containing water treatment processes would permit improvements in the existing methods and the development of new treatment techniques.

2.3 CONVENTIONAL CONTINUOUS-FLOW ACTIVATED SLUDGE PROCESS (ASP)

In general, activated sludge process (Figure 2.1) is an aerobic method for biological wastewater treatment. This process is based on the aeration of wastewater with biological growth. Part of this growth is then wasted and the remainder is returned to the system. Typically, biomass concentration in the aeration tank is varied between 2000 to 4000 mg/l. Several investigations have been done for treating the oily wastewater with the use of oil-acclimatized activated sludge where the oil is adsorbed on the sludge. The removal efficiency of the oil was found to be 80-82% (Scholz and Fuchs, 2000, Yamauchi et al., 1973; Hoshika et al., 1975).

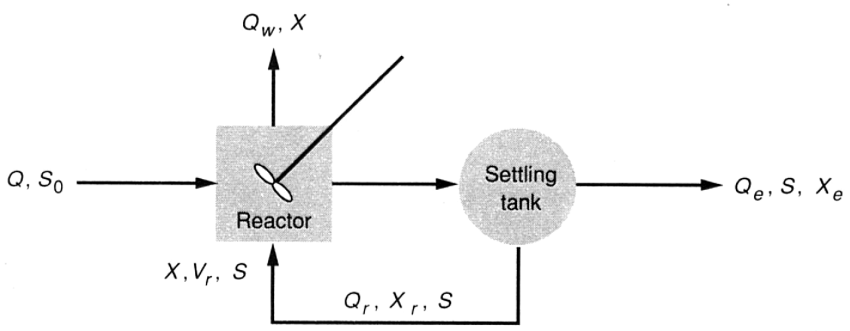

Figure 2.1: Schematic diagram of the complete-mix activated sludge process (Metcalf & Eddy, 1991)

Although the activated sludge process is widely practiced for biological treatment of oily waste, yet it was observed that poor sludge settleability resulted in poor maintenance of the ASP (Kumar et al., 2003). Galil N. and Rebhun M. (1990) found that the production of the volume of sludge was four times more than that produced from Rotating Biological Contactor system. The performance of activated sludge system in treating oily waste was also investigated by Sumi (2000).

2.4 CROSSFLOW MICROFILTRATION

Crossflow or tangential filtration is a process in which the formation of a filter cake is limited by a flow of the suspension parallel to the filtration surface. In this system, the feed stream is divided into two streams namely permeate or filtrate and the concentrate or retentate. On the other hand, in case of dead-end filtration, the suspension flows at right angles to the filter medium under the applied pressure. The particles are retained by the filter medium while the liquid flows through the filter cake and through the medium. Figure 2.2 shows a comparison of conventional dead-end and crossflow microfiltration. For treatment of oily waste by crossflow microfiltration, most of the research has been carried out mainly to investigate the effects of operating parameters i.e. transmembrane pressure, cross-flow velocity, and feed concentration on oil rejection as well as permeate flux. Zhu et al., 2000 reported that a membrane with pore size of 0.46 μm had rejection higher than 99% under 2.10 m/s crossflow velocity and 0.10 MPa transmembrane pressures. Bullon et al. (2002) showed that the emulsion viscosity and droplet size distribution depend on the shearing forces and transmembrane pressure.

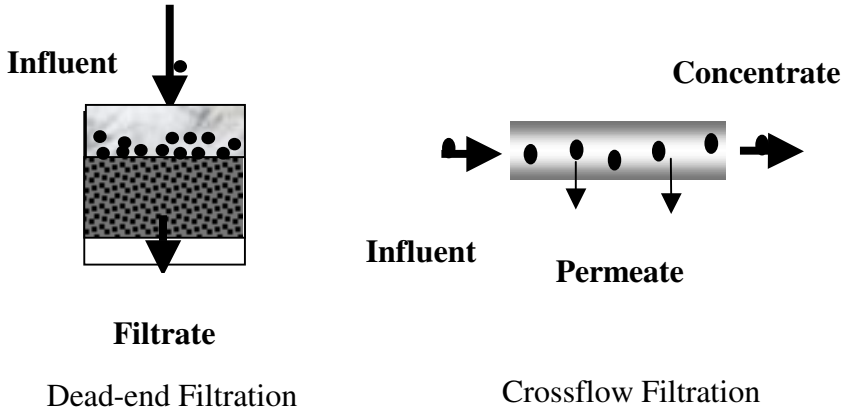

Figure 2.2: Comparison between Conventional and Crossflow Filtration

Mueller et al. (1997) found that increased oil concentrations in the feed decreased the final flux, whereas the crossflow rate, transmembrane pressure, and temperature appeared to have relatively little effect on the final flux. Fan and Wang (2000) investigated the effects of the feeding rate, the operating pressure difference and oil concentrations on membrane transport properties. The changes of water permeability with operating time were also tested. The results indicated that the oil elimination efficiency was over 95% and water permeability was about 0.11 x 10^{-4} to 1.1 x 10^{-4} m^3/ (m^2.s).

2.5 MEMBRANE BIOREACTOR (MBR)

The membrane coupled activated sludge process or simply membrane bioreactor concept is a combination of conventional biological wastewater treatment and membrane filtration. In an MBR installation this separation is not done by sedimentation in a secondary clarification tank, but by membrane filtration. Figure 2.3 summarizes the evolution of membrane use in wastewater treatment and demonstrates the basic differences in the treatment trails. To prevent fast clogging of the membranes, crossflow filtration is one of the suitable filtration process for solid concentration of 3000 mg/l and more as usually applied for the activated sludge process. The MBR process is useful when a long solid retention time is required, and physical retention and subsequent hydrolysis are critical (Knoblock et al., 1994). This process provides benefits over conventional activated sludge systems, including a small footprint, high effluent quality, reduced sludge wasting and production, reduced vulnerability to upsets, and improved biological degradation.

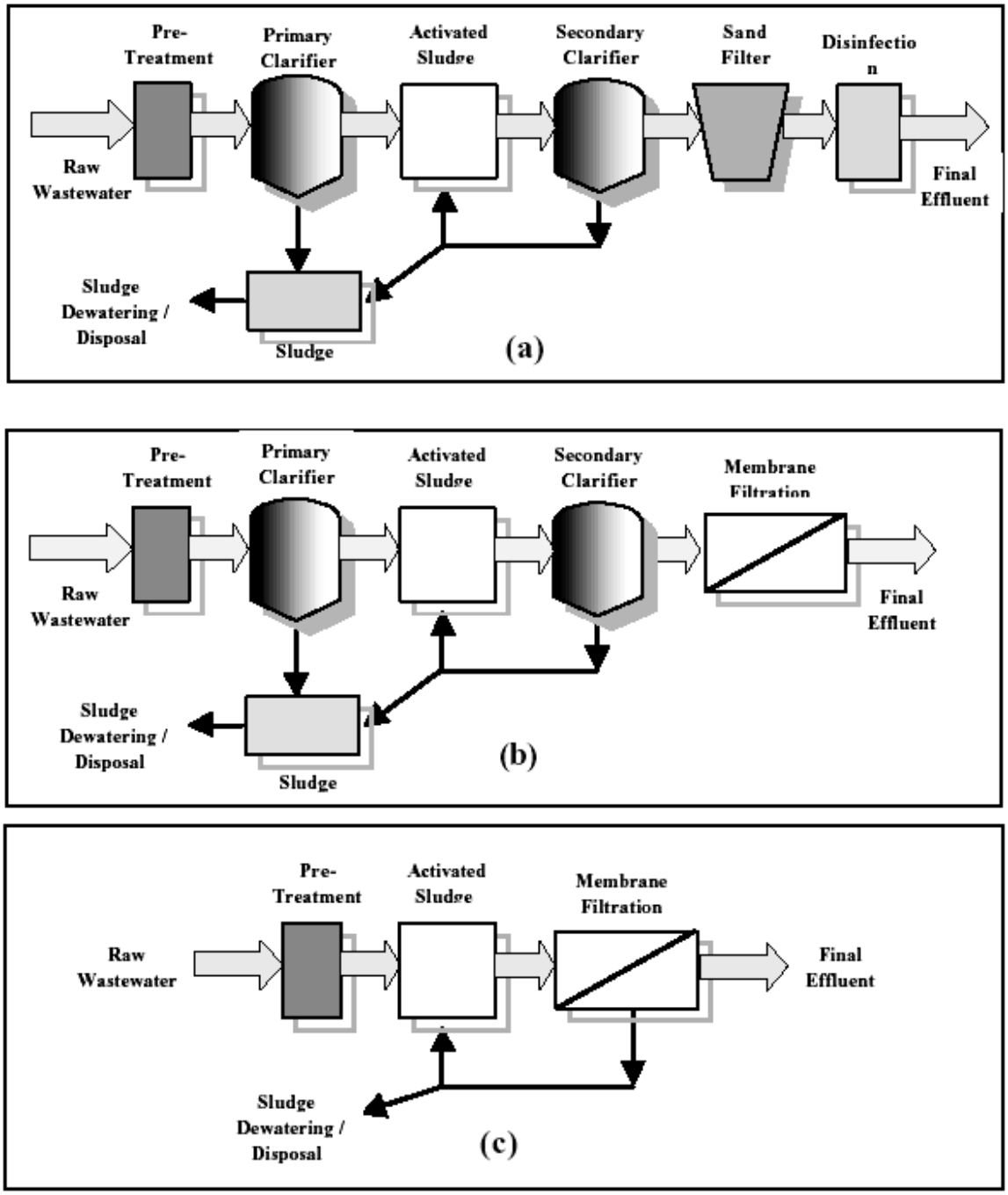

Figure 2.3: Flowcharts for (a) conventional wastewater treatment, (b) conventional treatment including tertiary membrane filtration, and (c) membrane bioreactors (Cicek N., 2002)

Also, primary ultrafiltration enhances system operational performance (Linden et al., 2003).

Despite the high-tech image of MBR today, the roots for this process were conceived from a humble beginning in the late 1970's as a simple concept of filtering biomass, utilizing available filtration technique at that time (Van der Roest, 2002). The filters of that time proved unreliable owing to fouling and breakage. But with the development of membrane technology, membrane bioreactor has nowadays a wide applicability in treating different types of wastewater. Elmaleh and Ghaffor (1996) studied the effect of different operational parameters in the treatment of oil refinery wastewater. Hydrocarbon aggregation on bacterial flocs was observed leading to larger particles with an optimal hydrocarbon/biological solids ratio. This induced a significant flux increase to 150 $l/m^2.hr$. Bloecher et al. (2004) developed an MBR to improve the quality of degreasing solutions from surface refining processes in the metal working industry. Permeate was found free of solid matter and hydrocarbon concentration was reduced by 85-90% (compared to the feed). Compared to conventional biological regeneration, a 5-fold increase in volumetric biodegradation rate was achieved due to the higher biomass concentration.

There are two alternatives with regard to the arrangements of the crossflow filtration unit, i.e. MBR with internal submerged membrane filtration (SM-MBR) and MBR with external membrane filtration that is termed as crossflow membrane bioreactor (CF-MBR).

2.6 CROSSFLOW MEMBRANE BIOREACTOR (CF-MBR)

A crossflow membrane bioreactor where the membranes are kept out side the aeration tank is normally generated by a pump that can also simultaneously create the transmembrane pressure difference for the filtration process. The supply of oxygen to the activated sludge and the required mixing of the activated sludge tank are guaranteed by a separate aeration, called “Biology aeration” (Gunder, 2001).

Scholz and Fuchs (2000) examined the feasibility of applying a CF-MBR to treat surfactant containing oil water emulsion. Trials in an MBR with a high-activated sludge concentration of up to 48 g/L showed that oily wastewater containing surfactants was biodegraded with high efficiency. The average removal of COD and TOC during the experiment was 94-96% for fuel oil, and 97-98% for lubricating oil respectively at a hydraulic retention time (HRT) of 13.3 h. Seo et al. (1997) also investigated the effect of HRT on the biodegradability of oil, where at an HRT of more than 10 days, the removal efficiency of oil was found to be more than 90%. The performance of the crossflow membrane bioreactor was also investigated by Daubert et al. (2003), Sutton et al. (1992) and Gaines et al. (2000).

2.6.1 Factors affecting the CF-MBR system

The performance of CF-MBR processes is affected by environmental and operating conditions as measured by the quality and quantity (flux) of the filtrate. Operating parameters associated with the characterization of the crossflow membrane bioreactor are explained with the help of Figure 2.4.

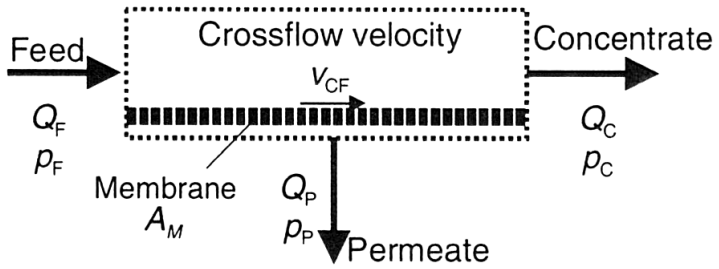

Figure 2.4: Operating parameters of the CF microfiltration (Gunder, 2001)

For characterization, both the flows (Q) as well as the pressures (p) of permeate and concentrate are indicated. Fan et al. (1998) investigated the effects of crossflow velocity, backwash interval and volume of flush liquid on the flux. At backwash interval of 30 minutes, backwash time of 20 seconds, backwash pressure of 2.4 bars and crossflow velocity of 3.5-3.9 m/s, flux of the MBR was found to be stabilized at more than 60 L/m^2h bar for more than 34 days.

2.6.1.1 Temperature

Some of the membrane materials are produced to operate at elevated temperature of more than 150^0C which might be suitable in places where careful cleaning of the product is essential, as in pharmaceutical and food processing industries. But as far as flux and rejection are concerned, the rise in temperature reduces the viscosity of the fluid to be filtered and thus becomes easier to filter through the membrane.

2.6.1.2 Transmembrane pressure difference (Δp_{TM})

The transmembrane pressure difference is the driving force behind the filtration process. In general, the transmembrane pressure difference is determined from the middle overpressure on the suspension side. It should be noted that the term "transmembrane" includes the membrane itself and the cake layer on the membrane surface.

2.6.1.3 Crossflow velocity (V_{CF})

By specifying the operating parameter for the crossflow velocity, only qualitative conclusions about the hydrodynamic situation near the membrane surface can be drawn. Higher velocities promote higher shear forces, which results in reducing the

tendency for a thicker deposit layer to develop. Therefore, the hydraulic resistance will be reduced; consequently, the flux rate will be enhanced.

The flux – Crossflow velocity relationship is usually described by the power law relation (Murkes et al., 1988).

$$J \alpha V^{n} \tag{2.1}$$

For V ($\longrightarrow$) 0 and n = 1.5

Theoretically at higher crossflow velocity the gel layer becomes very thin and the flux is limited by the resistance of the membrane material which gives a constant asymptote as shown in Figure 2.5. Then the flux will be proportional to the applied pressure as follows:

$$J = \frac{K_P \Delta P}{\mu_v R_m} \tag{2.2}$$

For V ($\longrightarrow$) ∞

Here, K_P = Permeability constant

R_m = resistance of the filter media

μ_v = Kinetic viscosity

Murkes J. (1988) and El-kebir (1991) found the value of 'n' to be 1.5 and 0.88, respectively.

2.6.2 Biochemical kinetics for CF-MBR system

The growth of a microbial culture is a complex phenomenon composed of a number of simultaneously occurring events. They can be grouped into the following three categories:

- Cell growth and substrate utilization

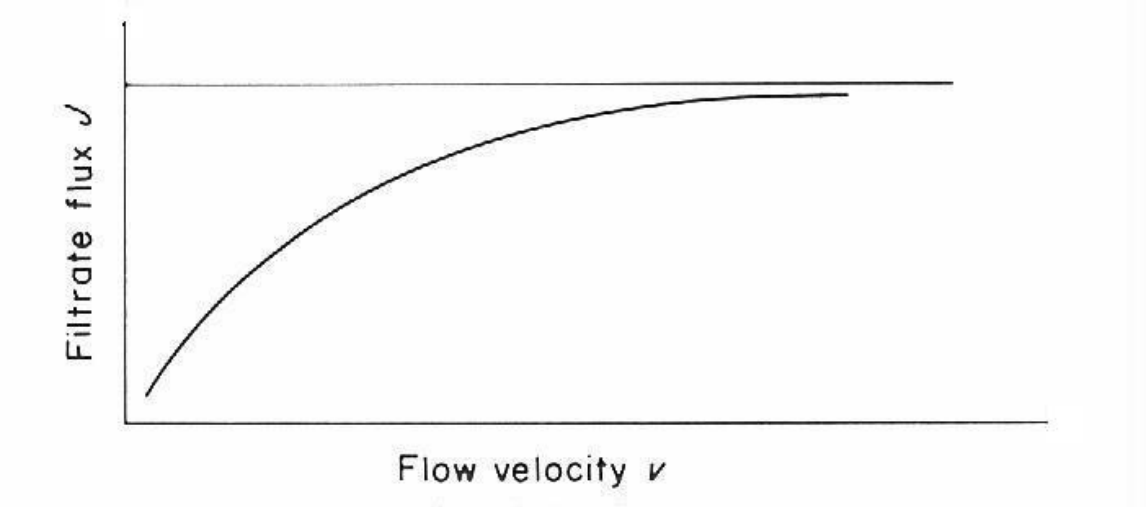

Figure 2.5: Influence of CFV on Flux rate. (Murkes J., 1988)

- Microbial death and viability
- Microbial decay

The basic equation that describes the interaction between the growth of microorganisms and utilization of the growth limiting substrate in the activated sludge process are based on the Monod (1949) equations. The Monod model is still the most commonly and widely used model for the study of the biokinetic coefficients.

Microorganisms require substrate for three main functions:

- To synthesize the new cell material
- To synthesize the extra cellular products
- To provide the energy necessary to drive the synthetic reaction and maintain concentrations of materials within the cell which are different from those in the environment.

Various environmental conditions can impact the values of the biokinetic constants. It needs to be emphasized that the system ecology and, consequently, the values of biokinetic constants vary with the change of environmental conditions and waste characteristics. Rozich and Gaudy (1992) reported that major factors affecting the biokinetic coefficients are

- Reactor growth rate: The rate at which a biomass is grown has a significant impact on the values of the biokinetic coefficients.
- Waste composition: the composition of wastewater has a significant effect on the ability of microbial populations to degrade target components.
- Toxicity: The toxic nature of a waste stream or other conditions can adversely affect the ability of a biomass to degrade wastes.

- Temperature: Temperature affects both the values of the constants and the types of wastes that can be treated.
- Population diversity: Microbial population diversity affects its ability to respond to different waste treatment situations.

Zhang et al. (2002) used a combinational approach with considering HRT as an evaluation index to discuss factors, such as maximum specific removal rate, K, saturation constant, K_s, maintenance coefficient m, maximum specific growth rate, μ_m and observed yield coefficient, Y_{obs}. He reported values of K and K_s for petrochemical wastewater treatment, as 0.185 and 154.2, respectively. In another study, Fan et al. (1998) reported a coefficient of COD removal, k, for petrochemical wastewater between 0.017 to 0.080 L/(mg.d).

Tellez et al. (1995) evaluated the biokinetic coefficients of New Mexico oilfield produced water. Using respirometric techniques for determination of the biokinetic constants, values of 1.37 mg/l and 0.136 h^{-1} were obtained for K_s and $\mu_{max,}$ respectively. Changes in cell yield were also evident, however, yields increased from 0.41 to 0.69 mg biomass/mg total *n*-alkane.

According to Suman Raj and Anjaneyulu (2004), typical values of half velocity constant (K_s), yield coefficient (Y) and endogenous decay coefficient (k_d) in industrial wastewater varies within a range of 850 to 5200 mg/l, 0.3 to 0.72 mg/mg, and 0.05 to 0.18 day^{-1}, respectively.

2.6.3 Role of HRT on the performance of membrane coupled activated sludge process

Hydraulic retention time (HRT) plays an important role in the removal of pollutant in the activated sludge system coupled with membrane. HRT can be defined as the residence time a water molecule spends before leaving the reactor. In case of activated sludge system, it is a common conviction that with the increase of hydraulic residence time, the pollutant removal efficiency of the system increases. A number of investigations have been done to find the effect of HRT on the performance of MBR in treating different types of wastewater.

Campos et al. (2002) investigated the treatment of offshore oilfield wastewater from the Campos Basin (Rio de Janeiro State, Brazil). The reactor was operated for 210 days, at three hydraulic retention times (HRT) of 48, 24 and 12 h. They reported that pollutant removal efficiencies (COD, TOC, phenols and ammonium) were not significantly affected by HRT. In the course of reactor operation, a well-adapted microbial consortium was developed, assuring good removal efficiencies even at the lowest HRT (12 h). Removal efficiencies of 65% COD, 80% TOC, 65% phenols and 40% ammonium were reported.

Tay et al. (2003) studied the effect of hydraulic retention time (HRT) on system performance in a MBR with a prolonged sludge retention time (SRT) for the treatment of industrial wastewater. HRTs of 6 days, 3 days, 1 day, 12 h and 6 h were investigated. The MBR process was capable of achieving more than 90% COD removal, which was almost independent of HRT. Based on the system performance at different HRT, an

optimal HRT of 12 h is suggested to optimize MBR system performance and to achieve economy in design and superior filtration performance in operation.

A laboratory-scale anoxic/aerobic membrane bioreactor (MBR) was studied by Wang et al. (2002) for treatment of industrial wastewater containing high carbon and nitrogen concentration. The performance of simultaneous carbon and nitrogen removals was studied when hydraulic residence time (HRT) of anoxic reactor was 5 h and HRT of MBR was 15, 10, 6 h, respectively. Obvious effects of HRT of MBR on system performance were not found.

Tanya et al. (1996) investigated the effects of hydraulic retention time (HRT) on activated sludge treatment of kraft pulping effluent with the help of a bioreactor. Varying HRT between 12 and 4 h and SRT between 5 and 15 d indicated that HRT had more of an effect on treatment performance than SRT. Longer HRTs led to improved BOD, COD and toxicity removals, while longer SRTs were not shown to significantly affect the performance. Shorter HRTs and longer SRTs led to significant increases in specific oxygen uptake rates (SOURs).

Visvanathan et al. (1997) reported that three different hydraulic retention times (HRT) of 12, 6 and 3 hours, corresponding to 0.16, 0.32 and 0.64 $m^3/m^2.d$ of permeate flux respectively, were investigated. Stable operation was obtained at the HRT of 12 hours. Decrease in HRT led to rapid formation of a compact cake layer on the membrane surface thus increasing the transmembrane pressure. All the experimental runs produced more than 90% removal of COD and TKN.

Diez et al. (2002) observed a removal of BOD_5 higher than 90% when HRT was varied between 16 and 6 h, but when HRT was less than 6 h, the BOD removal efficiency was found to decrease. Similar performance was observed for COD removal, which was about 60% when HRT was varied from 16 to 6 h. Removal of total phenolic compounds and tannin and lignin was seriously affected by HRT. When HRT varied from 7 to 16 h no toxicity was detected in the treated effluent. When HRT was less than 6 h, the system showed destabilizations and pH, COD, BOD_5 and suspended solids removal decreased.

According to Yoon et al. (1999), when the concentration of microorganisms are extraordinarily high (10,000 to 15,000 mg/l), the MLSS strongly controls the entire process regardless of any moderate changes of the operational parameters such as HRT.

2.6.4 Fouling of CF-MBR system

The decline in flux or permeation rate is believed to be the major hindrance of the wide implementation of crossflow filtration in the water and wastewater treatment industry. This decline in flux rate is attributed to the formation of a dynamic or secondary membrane on top of the primary membrane.

For the evaluation of the process and economic viability of membrane based filtration applications, flux stability is a significant component, which must be taken into consideration. The flux decline is caused by the continuous infiltration of fine particulate matter into the secondary layer or by the compaction of the layer.

Several techniques have been adopted to prevent the particles reaching the membrane such as

- Abrasives

- Filtration aids and coagulants
- Electrofiltration
- Ultrasonic fields
- Dynamically formed membranes
- Pulsed flow
- Hydraulic cleaning: The characteristics of hydraulic cleaning in crossflow membrane bioreactor were studied by Li et al. (1999) which showed that low trans-membrane pressure, high flow velocities along the membrane surface, and elimination of convective transport of penetrating liquid to membrane played important role in removing the fouling layer. Madaeni (2001) reported that the use of intermittency could provide flux enhancement and modest improvement in productivity.
- Backwashing: Backwashing can be carried out by forcing water or by blowing air through the membrane (Hoehn, 1998) and flushing it with the feed stream. Lee et al. (2002) reported that the steady-state flux when using backflushing was 1.5 times higher than that without backflushing. Faibish and Cohen (2001) and Cakl et al. (2000), reported the similar results. In another study Sondhi et al. (2000) reported 5-fold increase in steady state flux. According to Psoch and Schiewer (2004) the effect of backflushing decreases with growing layer thickness, due to pressure drop, and velocity loss.
- Chemical cleaning: Heinemann et al. (1988) investigated the use of H_2O_2, NaOH, Terg-A-Zyme (an alkaline enzyme active detergent), $NaBO_3.4H_2O$,

and protamine sulphate as cleaning chemicals in a crossflow microfiltration process. In another study, Bedwell et al. (1988) found that acid cleaning was highly effective in removing the inorganic portion of the dynamic membrane. Yijiang et al. (2002) carried out fouling removal from ceramic membrane by recirculating several chemicals such as 0.5M oxalic acid solution, 0.5M citric acid solution, 0.1M HCl solution and saturated $KHCO_3$ solution at 10 m/s CFV, 0.05MPa pressure, and 25^0C for 30 min, followed by a thorough rinsing with water. Gan et al. (1999) employed NaOH, HNO_3, H_2O_2, and Ultrasil 11 as the chemical cleaning agents for the removal of foulant from ceramic membrane. In this study 87% of the original water flux could be restored repeatedly after every chemical cleaning.

2.6.5 Advantages and disadvantages of CF-MBR System

There are several advantages associated with the CF-MBR, which make it a valuable alternative over other treatment techniques. In this system the retention of all suspended matter and most soluble compounds within the bioreactor leads to excellent effluent quality, capable of meeting stringent discharge requirements and opening the door to direct water reuse (Chiemchaisri et al., 1992). The possibility of retaining all bacteria results in a sterile effluent, eliminating extensive disinfection and the corresponding hazards related to disinfection by-products (Cicek et al., 1998). The sludge wasting and handling requirements in CF-MBR can be reduced significantly. Using membranes instead of settling tanks to clarify the reactor effluent enables MBR processes to operate at long sludge ages. The frequency of sludge wasting, removal of

material from the reactor for disposal controls the sludge age. In conventional activated sludge systems, the operating sludge age impacts the settling characteristic of the microbial population that develops in the biological reactor. The operating sludge age is often limited by the settling performance of sludge in the final clarifiers. Changes in the microbial population such as the development of pin floc or filamentous flock have little impact on the effluent quality (Zhang et al. 1996). Therefore, sludge wasting, and solids handling operations can be performed as a batch operation after relatively long intervals. The CF-MBR system requires little operators assistance, and, in general, little knowledge of the microbiological aspects of the process for successful operation. In conventional treatment, sludge handling and other changes in the activated sludge microbial populations can diminish the overall effluent quality. This possibility requires constant process supervision by qualified personnel. In the CF-MBR process, as the solids separation step is virtually independent of the microbial sedimentation, the supervision and expertise required are reduced. In this system the aeration is usually through a fine bubble diffuser, which offers much more efficient oxygen transfer and aeration cost is lower (20%) than the submerged MBR (90%) (Steven and mallia, 2001). Also for being driven by a differential head, the flux of the system is higher than that of submerged membrane bioreactor. The capital cost is also low when compared to other MBR systems.

The major disadvantage of CF-MBR is membrane fouling or membrane clogging. Fouling results from the accumulation and attachment of particulate and dissolved material at the surface of the membrane, which causes a significant resistance to filtration. Additionally, the presence of stringy material such as hair or rags would

significantly reduce membrane operation. This could be a major consideration for application without fine screens or a high degree of primary treatment.

CHAPTER 3

RESEARCH OBJECTIVES

The literature review section covered the basic principles of activated sludge process in general and membrane bioreactor in particular. This has shown that extensive research has been carried out in the areas of activated sludge process modifications. The status of the current research in the field of application of membrane filtration to activated sludge process is also distinct. Most of the research carried so far focused on operating pilot plants and studying the removal efficiencies for CF-MBR. In the study of removal efficiencies and stability of flux, variation of operating parameters such as crossflow velocity and transmembrane pressure were investigated. Some of the studies investigated the effluent quality at various HRTs. A relationship between COD and increase of MLSS and HRT in CF-MBR was also looked into. A number of studies focused on the fouling theory and cleaning of membrane, for smooth operation of the membrane bioreactors. Investigation to determine the biokinetic coefficient of the petrochemical wastewater was also completed. However information regarding CF-MBR biokinetic coefficient for treating refinery wastewater needs more work. Crossflow membrane bioreactor process started developing as a new process since late seventies, but still there is a lack of understanding of the interaction between the biological and filtration unit. Based on the above discussion, the main goal of this study is to investigate the kinetics of crossflow

membrane bioreactor for treating oily wastewater. The specific objectives of the study are:

A) To investigate the influence of Mixed Liquor Suspended Solid (MLSS) concentration on the biokinetic coefficients such as saturation constant (K_s), specific growth rate (μ), yield coefficient (Y) and endogenous decay coefficient (k_d). Two different values of MLSS i.e., 3000 and 5000 mg/l will be used for this purpose.

B) To study the effect of hydraulic retention time on the process performance at different MLSS concentrations.

C) To investigate fouling and cleaning technique of the crossflow membrane bioreactor system.

CHAPTER 4

MATERIALS AND METHODS

4.1 MEMBRANE FILTRATION UNIT

The membrane used throughout the experiment was made of ceramic and of hollow tubular configuration. It had 7.0 mm of inside diameter and pore size of 0.2 μm. The general characteristics of membrane are shown in Table 4.1. Each of the ceramic membranes was clamped to brass bend with the help of a short rubber tube. Five membranes were coupled in series and connected to the circulation pump at one end and to aeration tank at the other end (Plate 4.1 and Figure 4.1). A rectangular plexi glass tray of size 30 cm x 15 cm x 5 cm was used to collect permeate. This tray acted as the stand for the membrane unit as well as temporary storage of permeate which eventually was connected to the main permeate tank. The floor of the tray was designed keeping the fact in mind that permeate from every corner of the storage tank could be collected to the outlet point hence directed to permeate tank.

Table 4.1: Characteristics of the membrane

Configuration	Hollow Tubular
Material	Alumina (ceramic)
Pore size	0.2 μm
Outer diameter	10 mm
Inner diameter	7 mm
Length	5 x 20 cm
Cross-sectional area	38.5 mm^2
Total surface area	0.022 m^2
Effective surface area	0.019 m^2
Maximum thermal stability	120^0 C
Maximum filtration pressure	15 bar
pH range	1-14

Plate 4.1: Membrane filtration unit

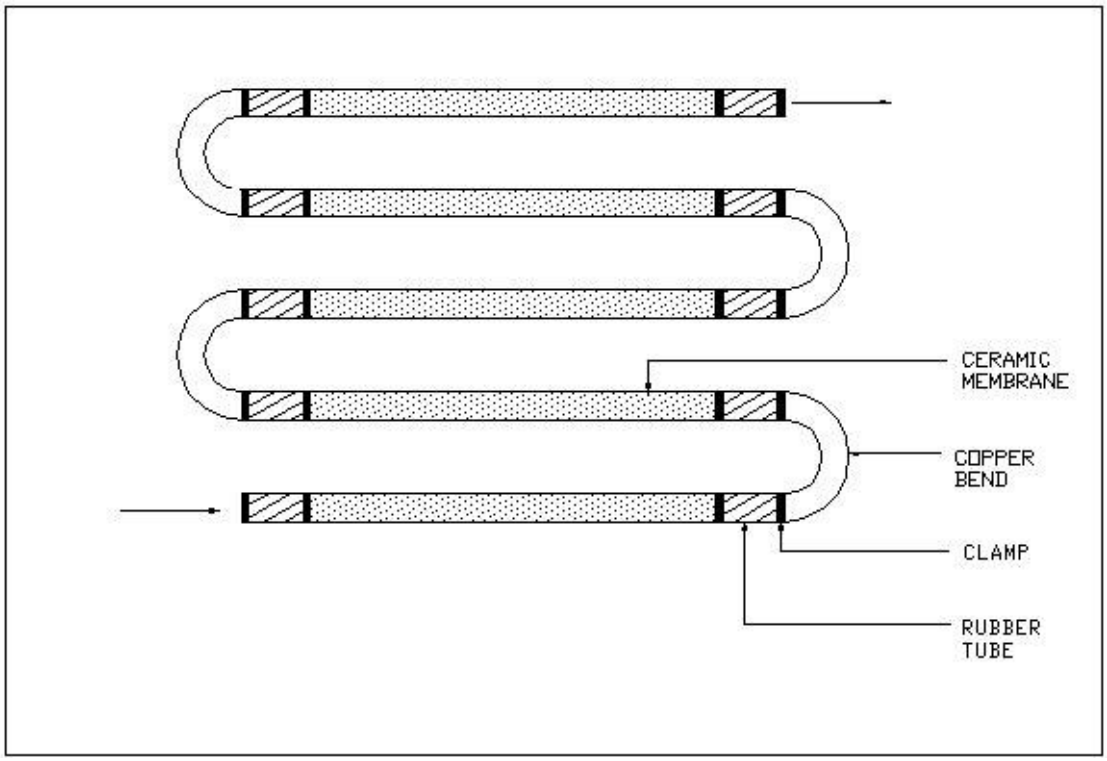

Figure 4.1: Schematic of membrane filtration unit configuration

4.2 DESCRIPTION OF THE CONTINUOUS REACTOR

The continuous flow reactor used in this study is shown in Plate 4.2, while Figure 4.2 shows the schematic diagram of the process. The experimental setup comprises the following:

Nutrient Feed Tank

This was a graduated, rectangular plexi glass tank of dimension 25cm x 25cm x 25cm. The capacity of the feed tank was 15 liters. Concentrated nutrient was diluted with tap water in this tank. The additional requirement of food in excess of the tank capacity was fulfilled by gradual supply of food to this tank with the help of variable speed peristaltic pump according to the necessity.

Oil Supply Tank

A polyethylene container with capacity of 450 ml was used as the source of oil supply (Plate 4.3). The container was capped in order to prevent the volatilization of the light part of the oily wastewater. Stirring arrangement was provided for the proper mixing of the oil.

Aeration Tank

This was a rectangular tank with dimensions of 52cm x 21cm x 35cm. Nutrient was fed to this tank from the nutrient feed tank through a float to control the level of the wastewater inside the tank to 20 liters. The tank had an overflow arrangement and a waste drain.

Plate 4.2: CF-MBR system setup

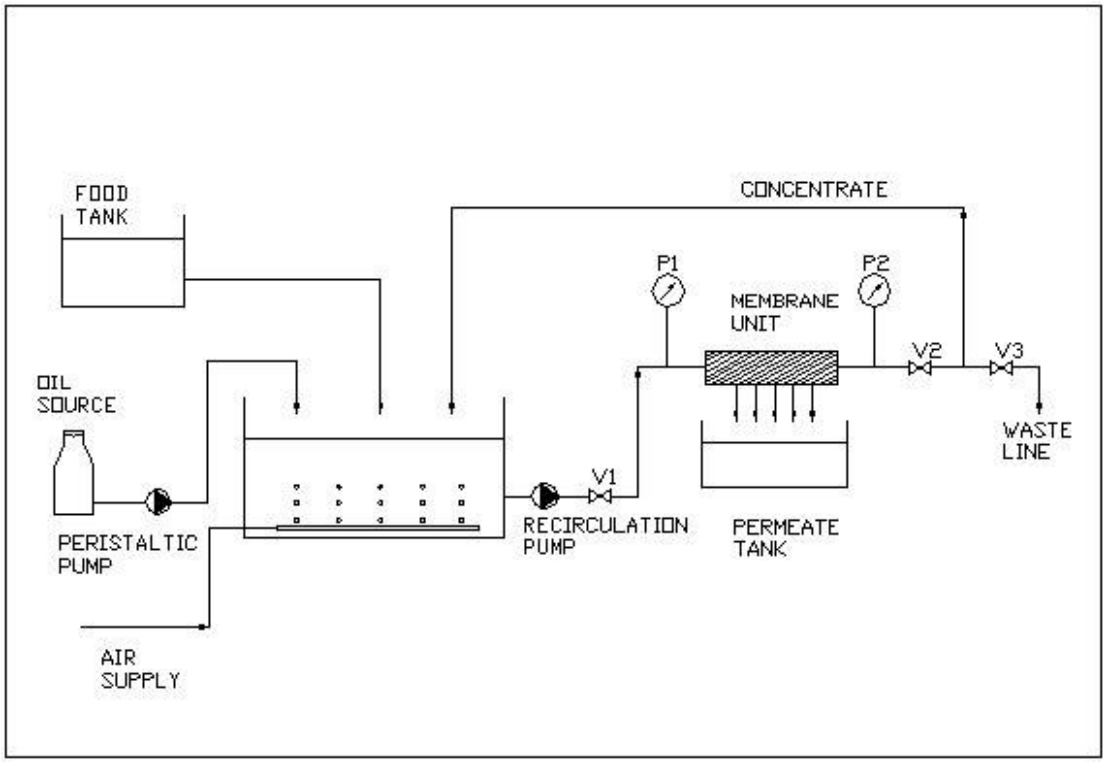

Figure 4.2: Flow diagram of CF-MBR system

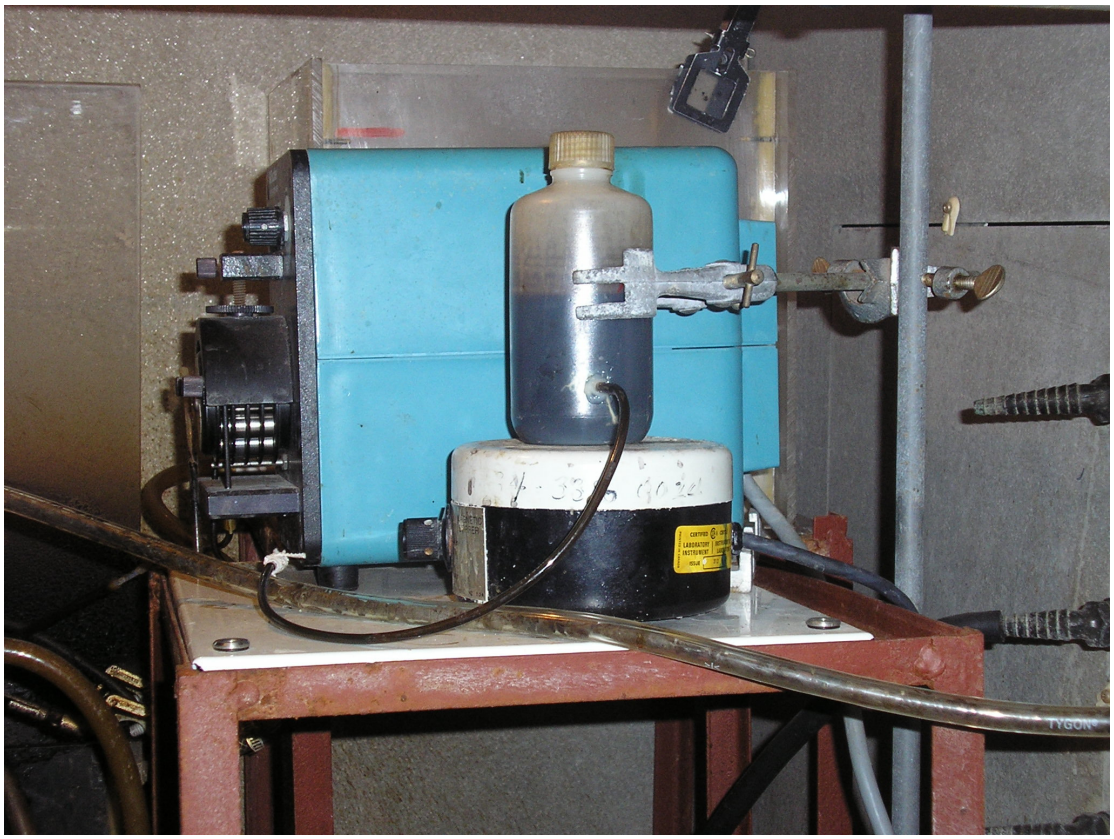

Plate 4.3: Oil supply tank

Oil Supply Pump

A BUCHLER peristaltic pump of variable speed was used to supply the oil from oil supply tank to the aeration tank. The oil was supplied intermittently at an interval of two hours and running for two minutes. The criteria for selecting the speed of the pump was based on the flow required to supply the desired amount of oil to the aeration tank per day. A GRASSILIN programmable timer was used to control the peristaltic pump for the desired intermittent oil supply.

Air Diffuser

Three cylindrical stone diffusers were used to keep the reactor contents under aerobic condition. Attention was paid in placing the diffusers in the reactor to maintain a uniform mixing of mixed liquor suspended solid (MLSS) in addition to supply oxygen. The diffusers were connected to the air injection line through tygon tubes.

Recirculation Pump

At the beginning of experiment, a centrifugal circulation pump with cast iron impeller was used. But this pump was replaced, due to some corrosion problem and another centrifugal pump with plastic impeller (DAVEY XF 192, 60Hz. 1.15 KW) was used.

Flow meter

A flow meter was attached to the delivery pipe of the pump to measure the flow delivered to the membrane filtration unit. The flow measurement was necessary in the calculation of crossflow velocity (CFV).

Valves

Three different valves V1, V2 and V3 were used in the continuous reactor system. V1 and V2 were used across the membrane separation unit for the purpose of controlling transmembrane pressure while V3 was used for controlling the waste line.

Pressure gauge

Two pressure gauges P1 and P2 were used across the membrane separation unit to measure the pressure before and after the filtration unit in order to calculate transmembrane pressure.

Permeate tank

A polyethylene container was used to collect permeate from membrane filtration unit. The container was graduated in order to facilitate the measurement of permeate volume.

4.3 INFLUENT SUBSTRATE

The oily waste used in this experiment was collected from a petroleum refinery. The oil content of this oily waste was determined as $160x10^3$ mg/l. The COD content was significantly high, which could not be determined by the conventional closed or open reflux titrimetric method. For this reason a modified approach of closed reflux titrimetric method for the determination of oily waste was needed to be investigated. Using the modified approach, the COD of the oily waste was determined as 370×10^3 to 2300×10^3 mg/l.

Essential nutrients were added to the bioreactor which consisted of glucose, peptone and east extract. The nutrients provided all the inorganics and micronutrients as well as nitrogen, phosphorus for the development of the biomass. The detailed composition of

the nutrient is shown in Table 4.2. Concentrated nutrient (100,000 mg/l COD) solution was prepared and stored in the refrigerator at 4^0C. Nutrient concentration of 500 mg/l in terms of COD was then prepared by diluting the concentrated nutrient with tap water in the nutrient feed tank.

The nutrient of 500 mg/l COD was continuously supplied to the reactor. The flow of the nutrient supply was matched with the permeate flow rate by keeping the water level constant in the reactor using a mechanical float.

The oil was supplied to the reactor intermittently with the help of a peristaltic pump at an interval of two hours and mixed completely in the reactor vessel. The COD concentration of nutrient was considerably less than that of oil (2.3×10^6 mg/l) but the volume used was significant. For that reason the COD contribution to the reactor by the nutrient could not be overlooked and associated in the influent substrate COD calculation. It should be mentioned in this regard that as the nutrient supply was continuous and the oil supply was intermittent, the influent COD calculation was based on the mass loading per day rather than the concentration throughout the study period. The influent substrate mass loading varied from 25 gm COD/day to 64 gm COD/day during the biokinetic studies.

Table 4.2: Composition of the synthetic nutrient (Kalyandurg, 2003)

Component	Contents in Stock Solution	Contents in Typical Feed Solution
Glucose, $C_6H_{12}O_6$	40,000	200
Peptone	40,000	200
Yeast extract	4,000	20
$(NH_4)_2SO_4$	32,000	160
KH_2PO_4	6,400	32
$MgSO_4.7H_2O$	8,000	40
$MnSO_4.6H_2O$	720	3.6
$FeCl_3.6H_2O$	40	0.2
$CaCl_2.2H_2O$	800	4
COD (mg/l)	100,000	500

4.4 MEMBRANE CLEANING

4.4.1 Cleaning agent

Membrane cleaning was achieved by using three different chemicals individually and in combination with each other. The cleaning agents used were

- CLOROX (5.25 % Sodium hypochlorite); Saudi Industrial Detergent Co., Dammam, Saudi Arabia.
- PERSIL (detergent); Detergent Industrial & trading Co., UAE, under license from Henkel (Germany).
- SUPERCLEAN (Acidic detergent); Saudi Industrial Detergent Co., Dammam, Saudi Arabia.

4.4.2 Cleaning procedure with PERSIL and CLOROX

When the flux decreased below the specified limit, the membrane unit along with the pump was separated from the bioreactor unit for the purpose of chemical cleaning. Before starting chemical cleaning, the pump and the membrane unit were cleaned with tap water (Plate 4.4). Tap water cleaning was conducted till the visual absence of any bacterial flocs in the outlet water. For the purpose of chemical cleaning, the membrane unit and the pump were connected to a 3.5 L jar containing the chemical solution. The cleaning solution was circulated and permeate was measured. The circulation was continued until the desired permeate obtained. After every chemical cleaning, the whole system was rinsed with tap water to confirm that there were no chemicals attached to the pump, membranes and tubes.

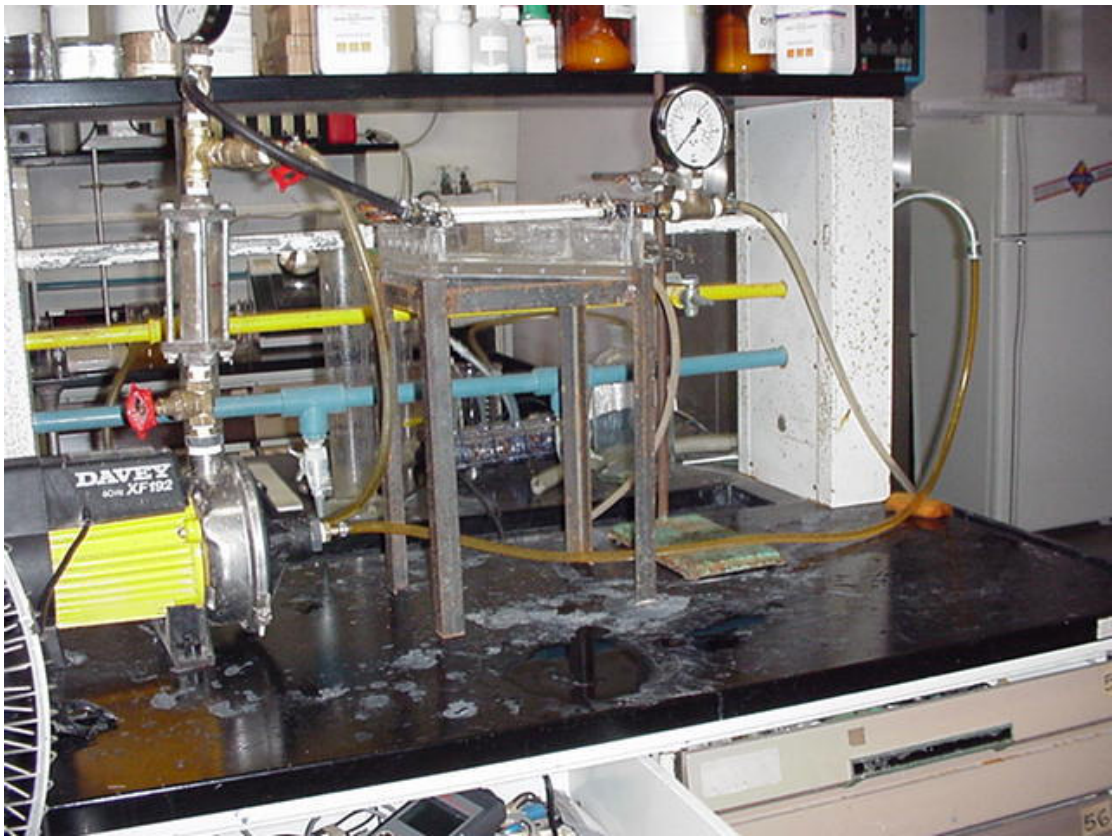

Plate 4.4: Cleaning with tap water

4.4.3 Cleaning procedure with SUPERCLEAN and backwash

In this procedure, only the membrane unit was removed from the system and rinsed with tap water to remove suspended solids attached to the membrane. The pH of the SUPERCLEAN solution varied from 1.41 to 1.48. A low speed peristaltic pump was used to circulate the solution for 10 minutes at a flow rate of 0.588 L/min. After the chemical cleaning, the membranes were rinsed with tap water for 15 minutes at a flow rate of 2 L/min. The membranes were backwashed for one hour after every chemical cleaning. For the purpose of backwash, one side of the membrane unit was blocked with the help of tubing and the other side was connected to the peristaltic pump. The membrane unit was immersed into a water bath and the suction was applied through the pump. In this way the pump sucked the water throughout the surface of the membranes in the reverse direction of usual filtration and thus symbolized the backwash cleaning process.

4.5 ANALYTICAL PROCEDURES

For the continuous reactor experiments, samples from the reactor and permeate were collected periodically and analyzed for different physical and chemical parameters, in accordance with the Standard Methods for the Examination of water and wastewater (Table 4.3).

Table 4.3: Analytical methods of different parameters

Parameter	Technique	Methods
Turbidity	Nephelometric	SM-2130B
pH	Potentiometric	SM-4500-H^+
MLSS	Filtration 4.5 µm	SM-2540D
DO	Oxygen Probe	SM-4500-O G
COD	Closed reflux	SM-5220C
BOD	5-days	SM-5210B
TOC	Combustion infrared	SM-5310B
Phenol	Mass spectrometric	SM-6420C
Oil & grease	Gravimetric	EPA 1664
Ammonia	Ion Selective Electrode	SM-4500-NH_3 D
Microbial	Heterotrophic Plate Count (HPC)	SM-9215B

4.6 SAMPLING FREQUENCY

Mixed Liquor Suspended Solid (MLSS) of the bioreactor was measured twice daily. The first measurement was done before wasting of the biomass to determine how much biomass need to be wasted to maintain steady state condition while the other one was done after the wasting. The COD of permeate was tested daily. Different factors related to the performance of the system such as dissolved oxygen, temperature and pH in the reactor and turbidity of permeate were measured. To assess the permeate quality, different parameters namely BOD, TOC, phenol content and oil & grease were tested once per week and ammonia was tested twice per week. Heterotrophic plate count in samples collected from the reactor tank and permeate was done three times during the experiment.

4.7 EXPERIMENTAL PROCEDURE LAYOUT

One of the essential parts of the study was to acclimatize the microorganisms (MO) to the oily waste. Return activated sludge was brought from Saudi Aramco wastewater treatment plant to be used as the seed for building the acclimatized microorganism culture and the oily waste from petroleum refinery.

The nutrient and oil were added to the bioreactor and mixed completely. The nutrient was supplied continuously while the oil was pumped intermittently for two minutes every two hours. The circulation pump was used to pump the MLSS to membrane separation unit under pressure, where a part of water was permeated through the membrane and the mixed liquor was concentrated in the bioreactor. From the membrane unit, the permeated water was collected in permeate tank.

The experimental investigation in this study consists of two phases. In the first phase, the biokinetic coefficients were determined for MLSS concentrations of 5000 and 3000 mg/l, by operating the system at various sludge retention times (SRT) and by allowing (at each stage of SRT) a steady state condition to prevail. In the second phase, the effect of HRT on the removal efficiency of COD was investigated for both MLSS concentrations.

At the beginning of the study, an MLSS concentration of 5000 mg/l was attained and maintained under steady state conditions. A steady state condition was achieved when fairly constant biomass growth and filtrate COD were obtained (Standard Deviation 5%). Sludge was wasted daily to maintain steady state conditions. Then, by increasing the organic mass loading (gm COD/ day) and controlling the SRT, a second steady state condition for same MLSS concentration was achieved and biomass as well as effluent substrate concentration were recorded. Similarly, the third and fourth steady state points were obtained. The kinetic coefficients were determined by plotting these parameters at steady state conditions. Next, the biomass was reduced to 3000 mg/l and similar analyses were carried out after attaining steady state conditions at each of the specified substrate condition. Flux and transmembrane pressure were also measured to assess the performance of the crossflow membrane bioreactor (CF-MBR) under different MLSS concentrations.

In the second phase, the experiment was run to find the effect of three different HRT on the COD removal efficiency of the system. The HRT was controlled by controlling the flux at different crossflow velocities.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 PERFORMANCE OF CF-MBR SYSTEM

5.1.1 Acclimatization

As stated in the previous chapter, microorganisms were acclimatized to the nutrients and the oily waste. The nutrients used for the acclimatization process were glucose-peptone based synthetic substrate in addition to the oily waste from a petroleum refinery. At the initial stage of acclimatization, higher concentration of nutrient and lower concentration of oil were used. With the progression of time, the oil concentration was increased to reduce the dependency on the nutrient which was not fully eliminated. The biomass was acclimatized to the nutrient and oil for five months. This period of acclimatization was not necessary, but was a result of the delay experienced in constructing the experimental setup. However, when the sludge was put in the system, it was already acclimatized to the feed.

5.1.2 Hydraulic Performance

This section presents a discussion on the results of the performance of the membrane unit and problems experienced while carrying out the experimental work. The performance was assessed under the influence of various operating conditions on flux rate of the membrane unit.

In the study of crossflow filtration system, the selection of pump plays an important role. The pump is responsible for maintaining sufficient transmembrane pressure as well as flow, which are directly related to the variation of flux. At the beginning of this study (1^{st} to 12^{th} day), the pump with cast iron impeller was used for the recirculation purpose. Usually this type of pumps, when not in operation, is affected by corrosion in the impeller. In this corroded condition, when the pump was used to feed the biomass to the membrane unit, enormous quantity of corrosion came in contact of the membrane and caused rapid membrane fouling. This phenomenon can be observed in Figure 5.1, where the variation of flux during the whole study period is shown. The above mentioned reason might be the cause of lower initial maximum flux (65 L/m^2/hr on 1^{st} day) than the later part of the study period (123, 123, 140 and 114 L /m2 /hr on 13^{th}, 64^{th}, 68^{th} and 88^{th} day respectively) when the pump with plastic impeller was used. The variation of flux showed a decreasing pattern which can be attributed to membrane fouling. A pre specified flux of 35 L/m^2/hr was used as the critical flux. When the flux dropped below this critical level, the membrane unit had to undergo chemical cleaning which is described in subsequent section. The system continued for a maximum of 50 days without the chemical cleaning.

For the determination of MBR performance, hydraulic retention time is a key issue. The variation of HRT during the biokinetic coefficient determination period is shown in Figure 5.2. Although in kinetic coefficient study, HRT is an important factor, yet in the current study, HRT could not be used as a controlling factor because of the limitation in the experimental setup. However the system was operated at an average HRT of twenty one hours. The sharp increase in HRT (Figure 5.2) was because of sudden reduction of flux due to the fouling of membrane and was not accumulated in the average HRT calculation as this peak HRT lingered only for a short period of time.

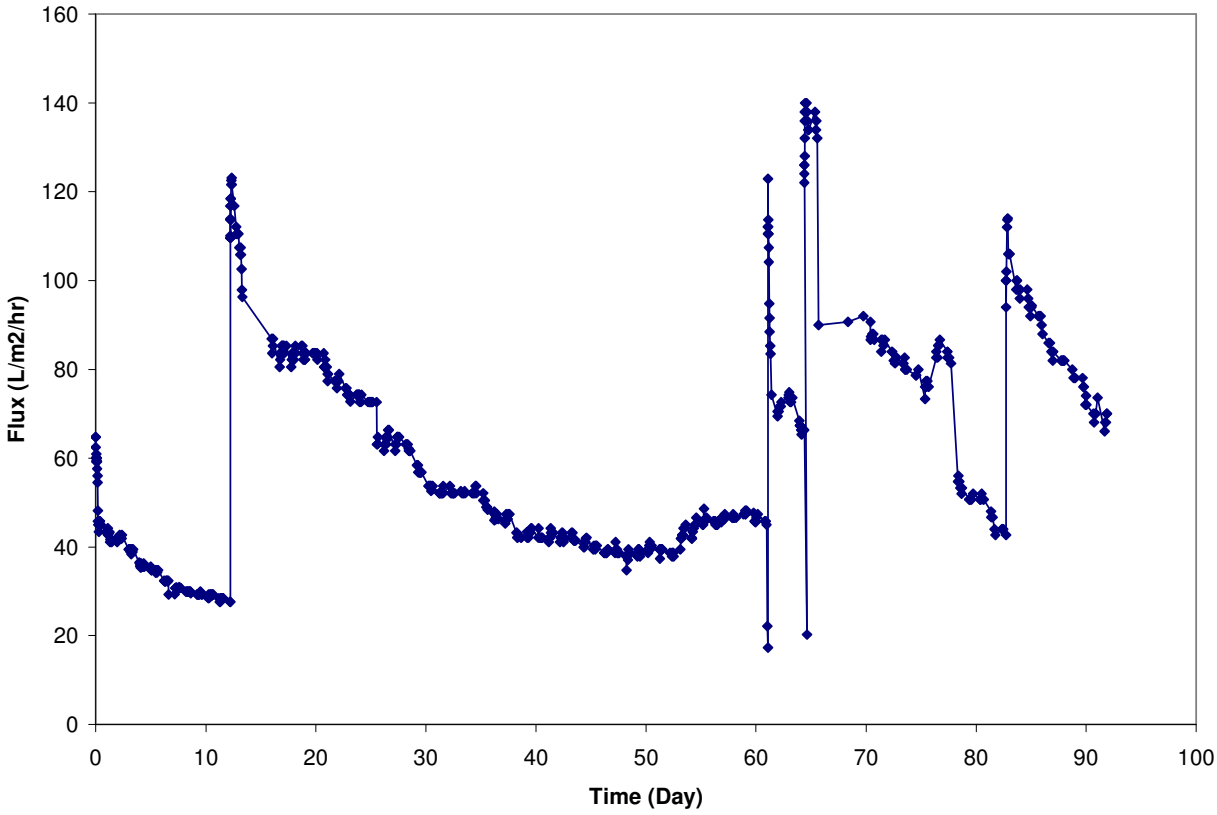

Figure 5.1: Variation of Flux with time

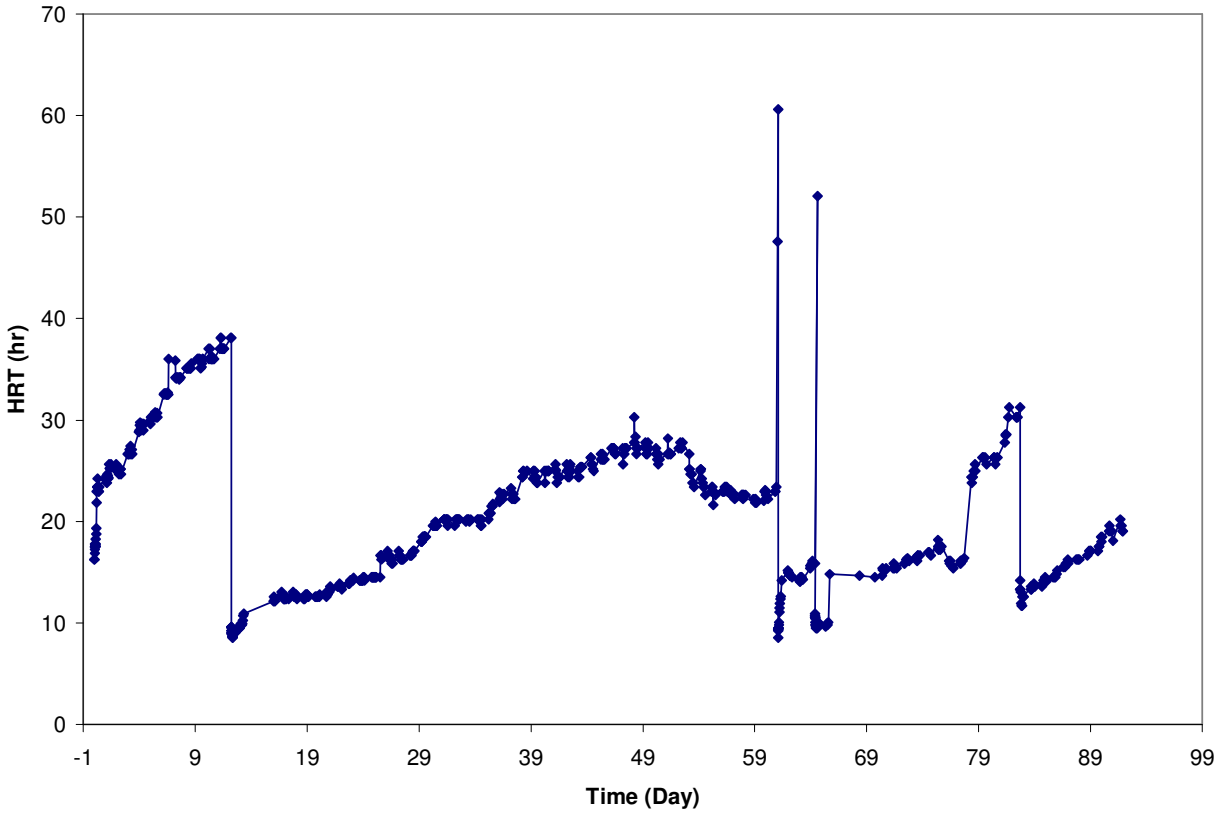

Figure 5.2: Variation of Hydraulic Retention Time (HRT) with time

Figure 5.3 represents the effect of transmembrane pressure on the variation of flux. Almost all over the experimental period it was observed that the flux increased with the increase of pressure and vice versa. One of the reasons behind this fact might be the use of centrifugal pump, where the pressure is proportional to flow. This phenomenon can be observed in the Figure 5.3 where, before the 55^{th} day the flux had a decreasing pattern, which increased suddenly when the pressure increased from 14.5 to 15.9 psi. So, in this case the flux can be called the pressure dependent. But some exception was also found. From 89^{th} to 97^{th} day the flux declined exponentially even though the pressure remained constant. This might happen solely because of fouling of the membrane and the flux can be described as pressure independent. Throughout the kinetic study period, the transmembrane pressure varied within a range of 11.5 to 24.0 psi.

Figure 5.4 represents the variation of effluent turbidity. The figure shows that the turbidity of the effluent was maximum at the beginning (1^{st} day) of the experiment and rapidly decreased to steady state. The reason behind this can be explained in the way that at the beginning of the run, the pore size of the membrane was wide and solid could easily pass through the membrane pores. But as the process continued, a secondary layer started developing on top of the membrane, resulting in a reduction in pore size of the membrane and as a consequence the rejection increased. However, this rapid decrease in turbidity was not observed when the membranes were reused after cleaning.

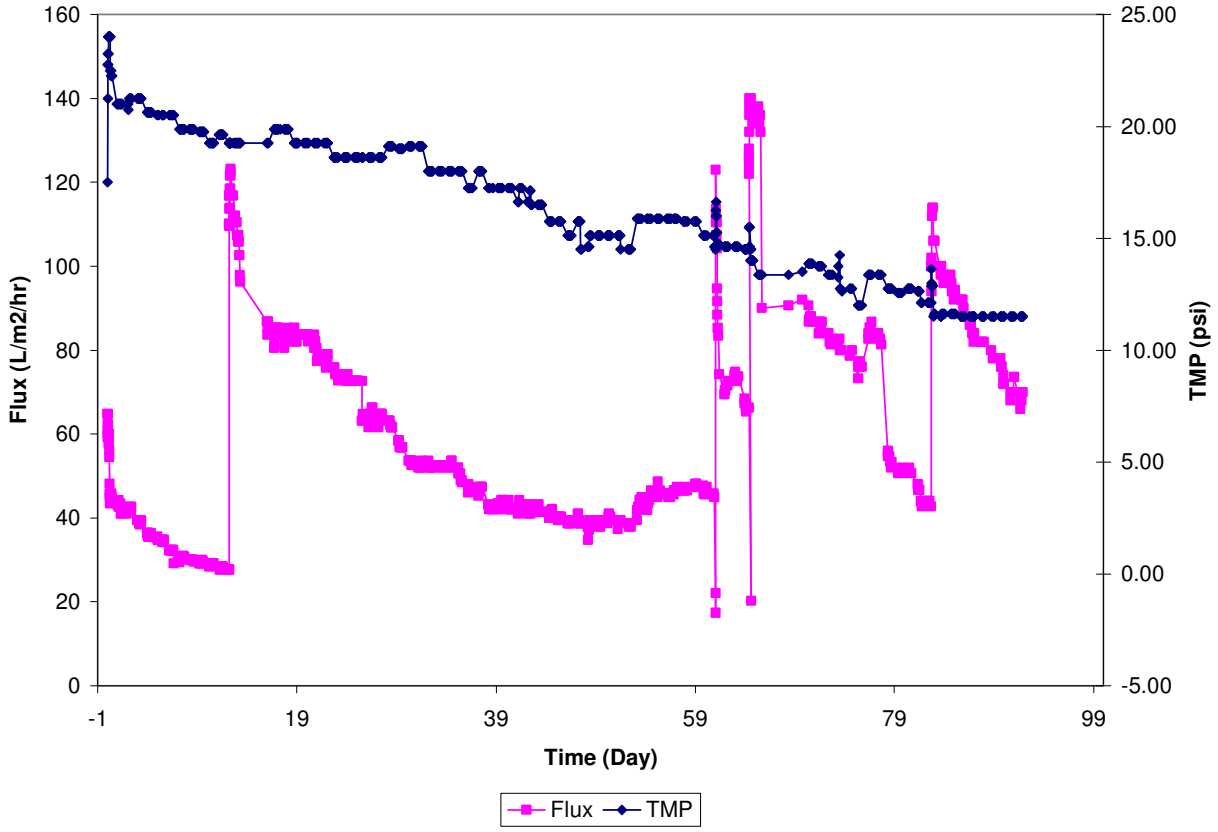

Figure 5.3: Effect of transmembrane pressure on flux

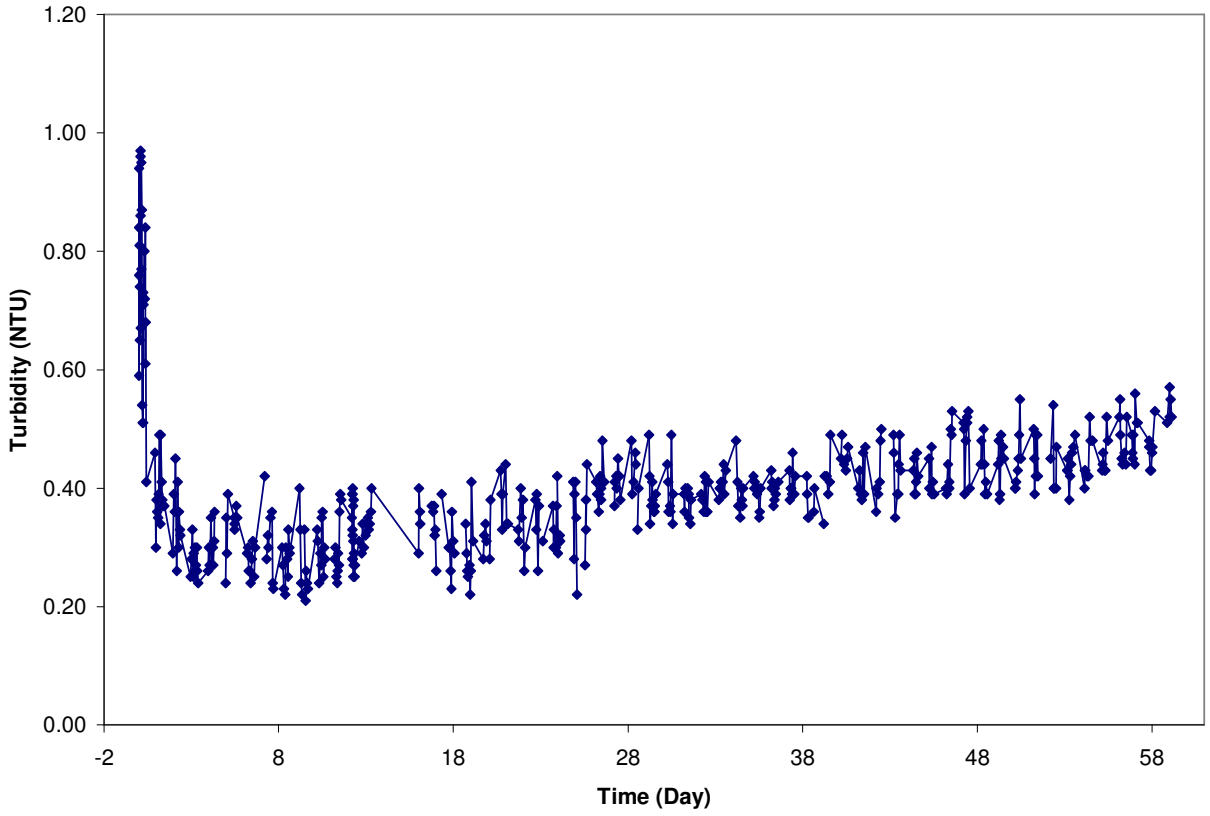

Figure 5.4: Variation of turbidity with time

The turbidity increased slightly after 28th day which might seem to be contradictory to the explanation that with time rejection increases. But the reason behind this increase was some powdered type substances which accumulated on the body of membrane connection accessories (Plate 5.1). Occasionally this powdered substance came to the effluent which could not be resisted. However, the effluent turbidity was less than 0.6 NTU with an average of 0.4 NTU.

Sometimes at the beginning of the run after cleaning, the flux decreased sharply with time, which is a classic phenomenon in membrane filtration, but later the flux started to recover slightly. This increase in the flux could be attributed to the increase in temperature. It was observed that the temperature of the mixed liquor at the beginning of the run was at room temperature and as the recirculation continued, the temperature of the liquor increased to the range of 38 to 47^{0}C (Figure 5.5). This increase in temperature resulted in a reduction in viscosity of the fluid and might also have expanded the CP layer, thus allowing more fluid to pass through.

To keep the aerobic condition in the bioreactor, air was supplied continuously and the dissolved oxygen was measured frequently using the DO probe. The DO level was never less than 4.0 mg/l (Figure 5.5) which shows that the aeration provided in the reactor was in excess of DO requirement. On the other hand, this air supply was needed to keep the reactor contents in suspension. The pH of the biomass in the reactor was in the range of 6 to 8 (Figure 5.5), which ascertains the suitable condition for the biomass growth.

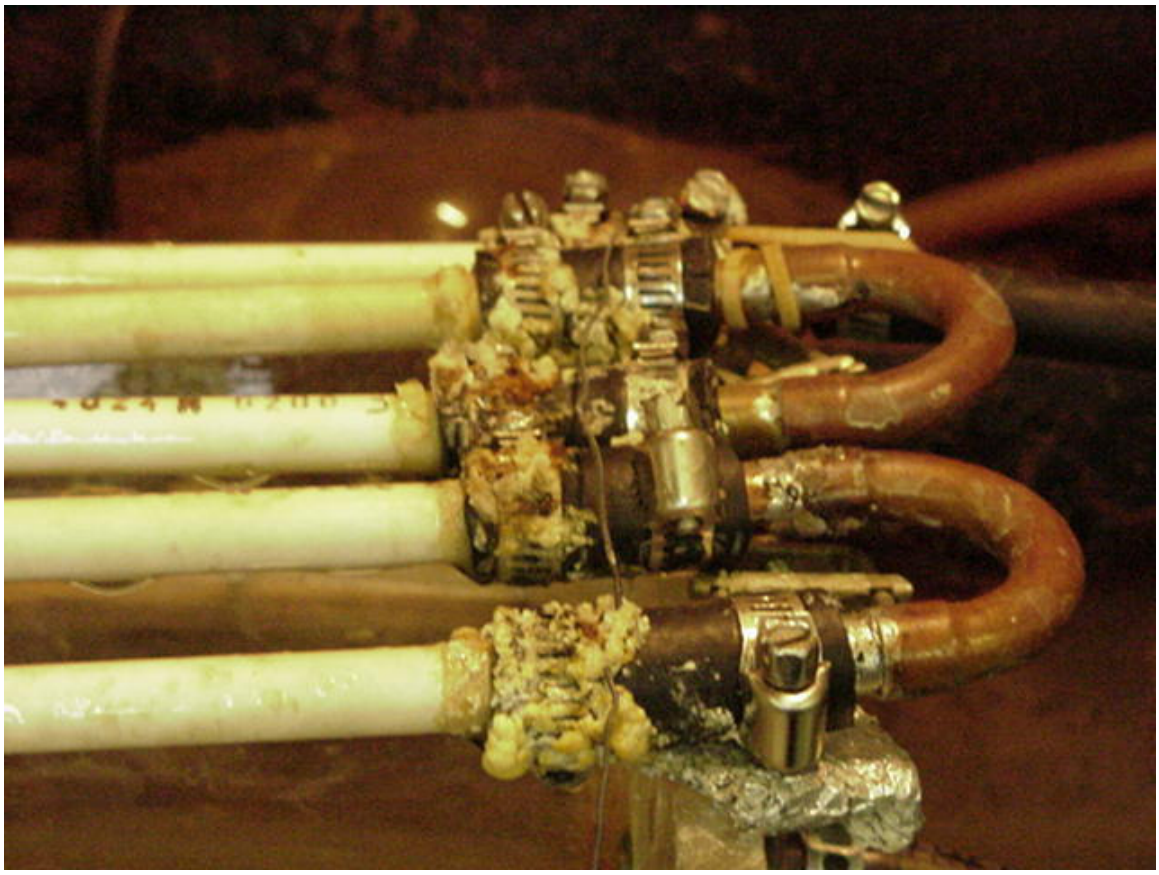

Plate 5.1: Accumulation of powdered substances on the membrane connection accessories

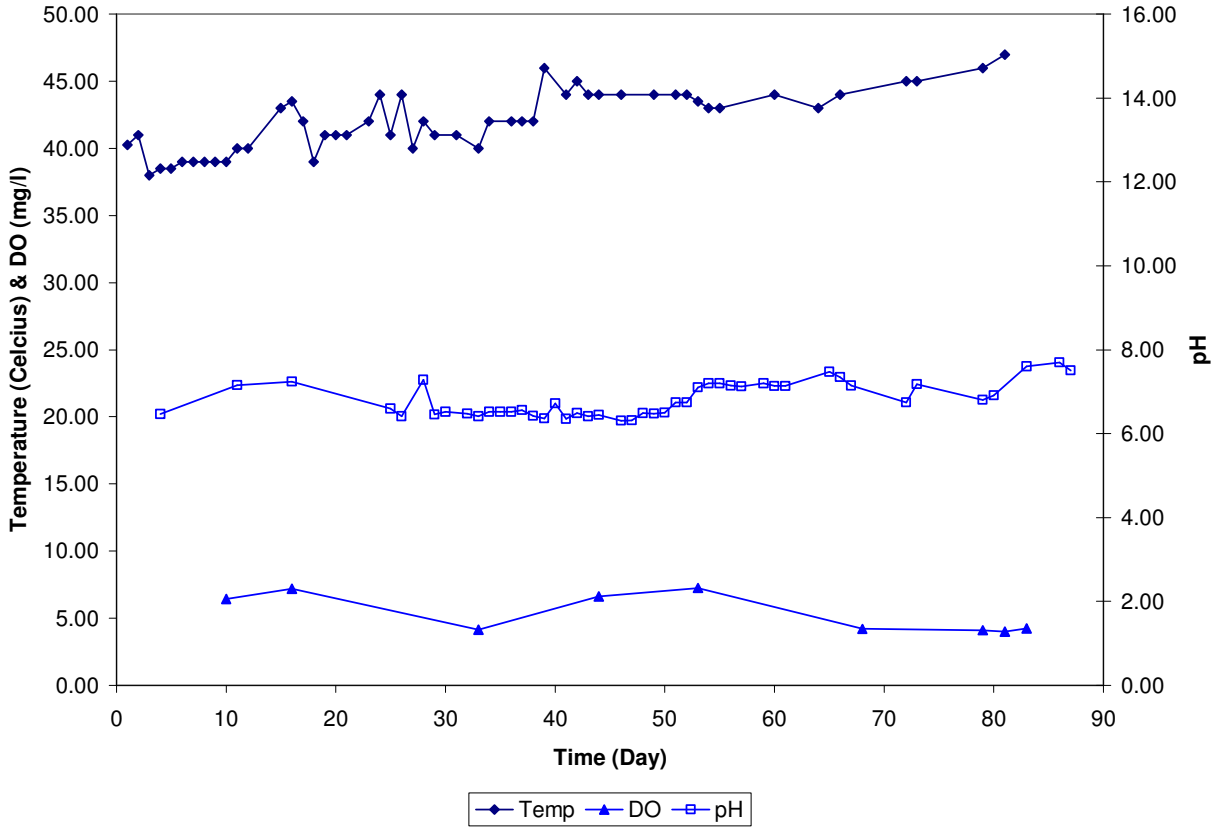

Figure 5.5: Variation of Temperature, Dissolved Oxygen and pH

5.1.3 Cod Removal Performance

The performance of the CF-MBR was studied to assess the ability and stability of the system to provide the required COD removal. The performance of the system at two different MLSS concentrations is presented.

At the beginning of the study, the MLSS concentration was chosen to be 5000 mg/l. The liquor was light brown in color and made up of dispersed non flocculent particles. Figure 5.6 represents the variation of influent and effluent mass loading over the biokinetic study period at MLSS 5000 mg/l. The influent mass loading presented in the figure is the average of the mass loading applied during a certain period of time needed for getting the steady state condition at each adopted loading. For this reason, the variation of influent substrate can be clearly noticed by steady horizontal line. To keep resemblance, the effluent loading is also presented in average value. The sharp peaks in the permeate COD are due to the sudden increase in influent COD concentration. Occasionally it was found that the increase of effluent COD due to the change of influent loading was not rapidly responding and was apparent after one or two days. On 42^{nd} day, the effluent loading is noticed to be less than the previous days, although the influent loading increased and the effluent COD concentration remained same. This was due to the calculation of effluent mass loading with less volume of effluent (due to low flux) at this higher adopted loading stage. The influent mass loading varied from 24 to 67 gm/day.

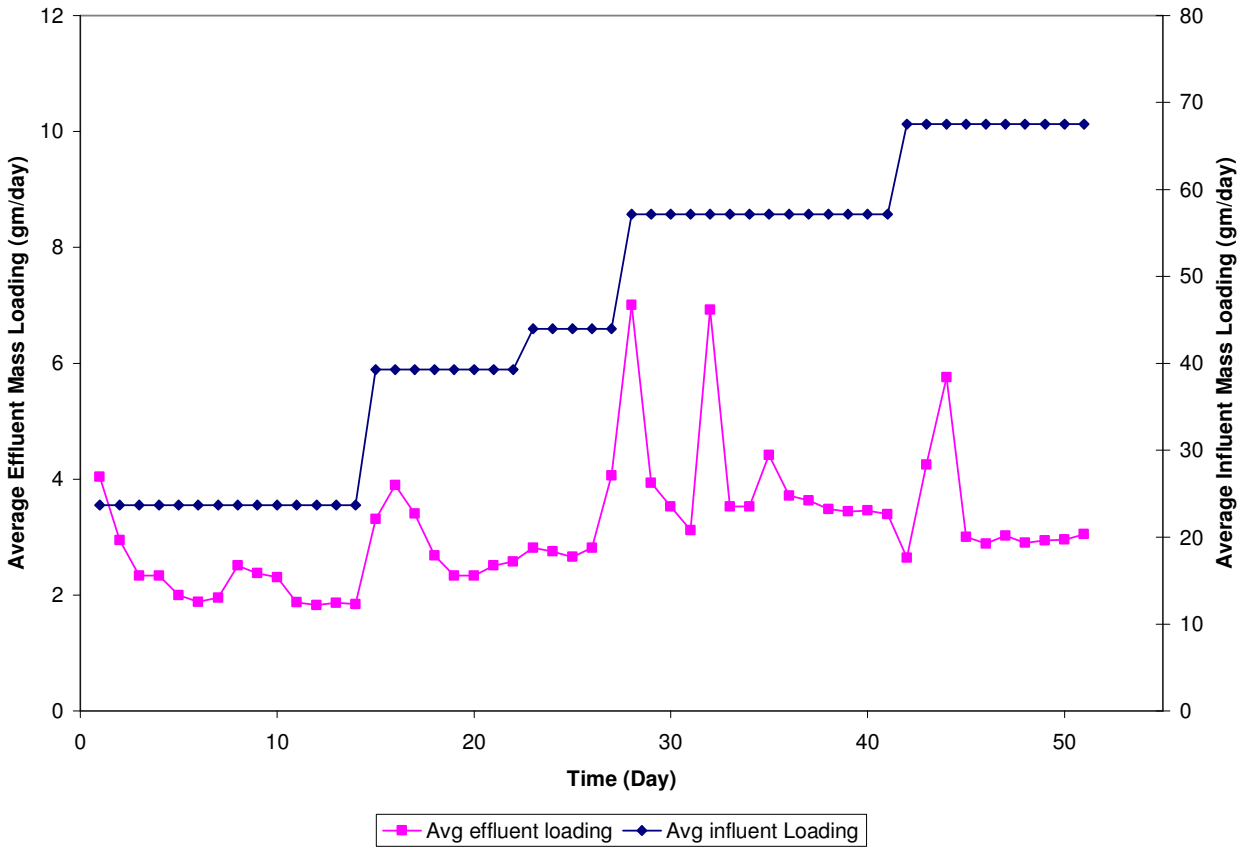

Figure 5.6: Variation of Average Influent and Effluent Organic mass loading at MLSS 5000 mg/L with Time

Figure 5.7 represents the COD removal efficiency of CF-MBR. The COD removal efficiency ranged between 82% and 97% with an average of 93%. The sharp drops in efficiency are due to the sudden increase of influent mass loading.

The biomass content of the reactor was measured twice a day. One measurement was to monitor the MLSS concentration present in the reactor and then calculate the volume of MLSS to be wasted in order to keep the suspended solid at around 5000 mg/l. The other measurement was taken after the wasted volume was replaced by tap water in order to check the remaining MLSS concentration. That is the reason Figure 5.8 has crisscross shape. In this regard it should be mentioned that the error associated for replacing the MLSS by tap water was not calculated in this study. In Figure 5.8, a decreasing shape of MLSS variation is observed during the period of 29^{th} to 34^{th} day. The reason behind this is excessive foam caused in the reactor. The foam was full of attached biomass (Plate 5.2) and carried a considerable amount of MLSS out of the reactor.

Sludge retention time was used as a controlling parameter in the growth rate of biomass during the kinetic study period. Figure 5.9 shows the variation of sludge retention time during the study period at MLSS 5000 mg/l. The sludge retention time varied from nine to hundred sixty days during the study period. The horizontal line joining the points having same values are due to the fact that the MLSS was not wasted for those days. When the MLSS was found adequate to be wasted, the SRT was calculated taking the average of previous non wasting days and distributed the value equally. It can be seen that at each loading, initially the SRT is high but with the progression of time it decreases.

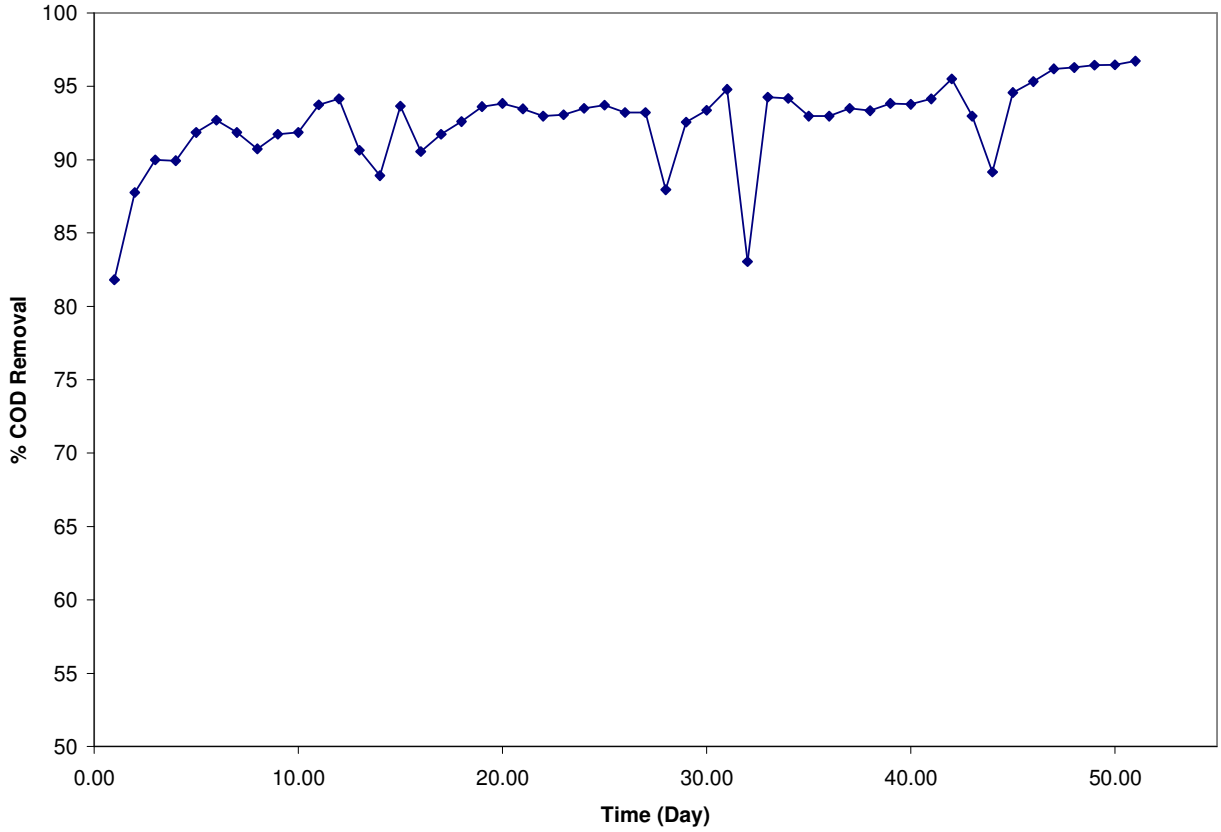

Figure 5.7: COD Removal Efficiency at MLSS 5000 mg/L with Time

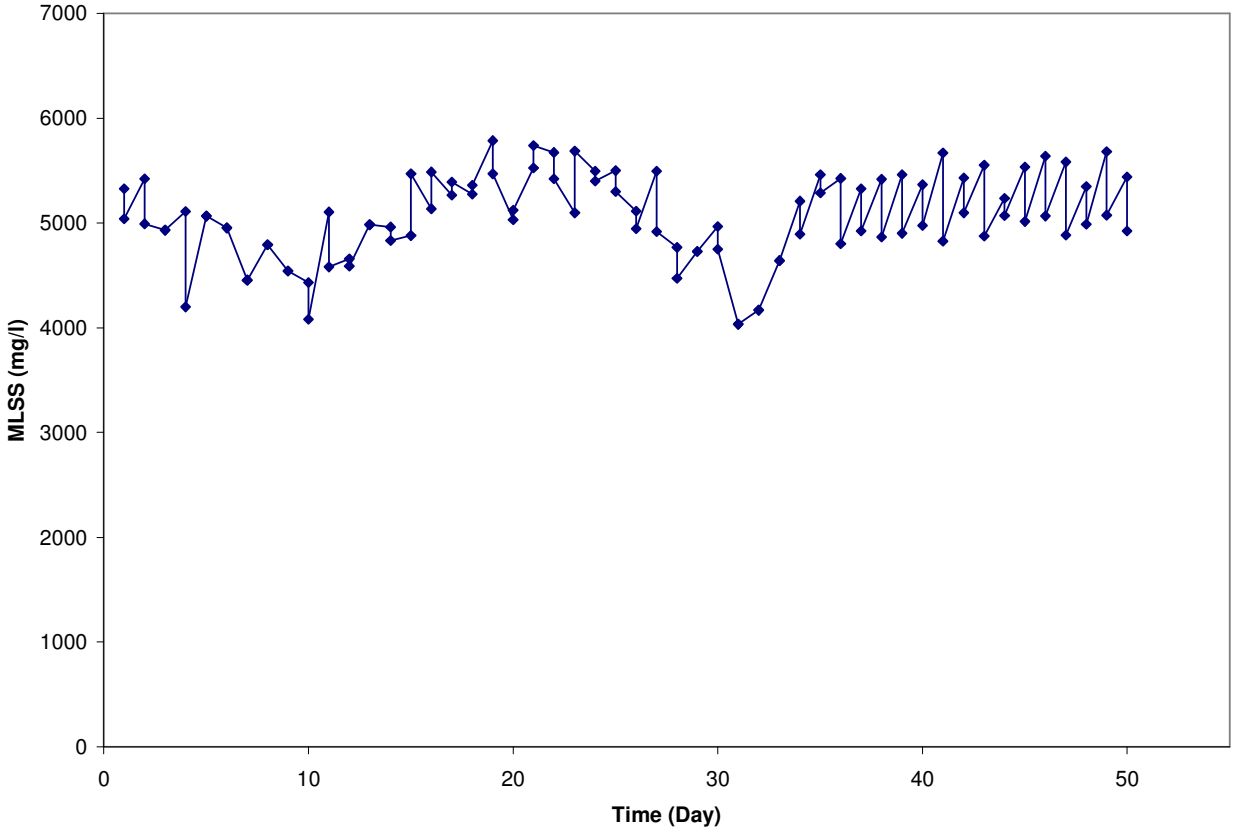

Figure 5.8: Variation of MLSS concentration with Time for MLSS 5000 mg/L

Plate 5.2: Excessive foaming in the reactor

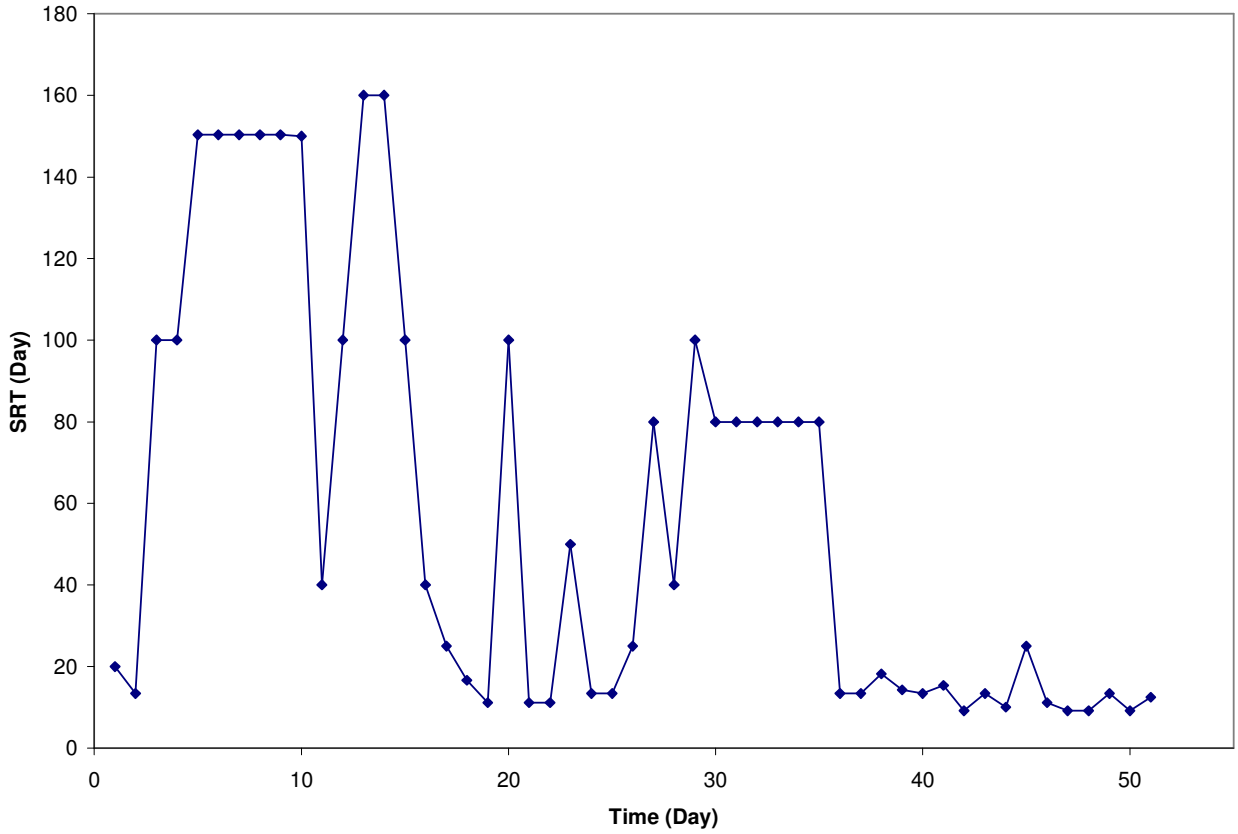

Figure 5.9: Variation of Sludge Retention Time (SRT) at MLSS 5000 mg/L with Time

Results from the unit, when operated with the MLSS 3000 mg/l is presented in the Table B2 (Appendix B) and graphically shown from Figure 5.10 to 5.13. Generally the performance was impressive with changing the influent mass loading from 30 to 65 gm/day (Figure 5.10). The average COD removal efficiency was 94% (Figure 5.11). The sludge retention time varied from four to fifty days with an average of twenty five days.

From the above discussion it can be concluded that during the biokinetic study period at both the MLSS concentrations, high removal efficiency (93% and 94% for MLSS 5000 and 3000 mg/l, respectively) was observed and the removal efficiency was not improved with increasing the MLSS concentration (from 3000 mg/l to 5000 mg/l). At MLSS 3000 mg/l, the system was operated at sludge retention time of twenty five days which was almost half of that at MLSS 5000 mg/l.

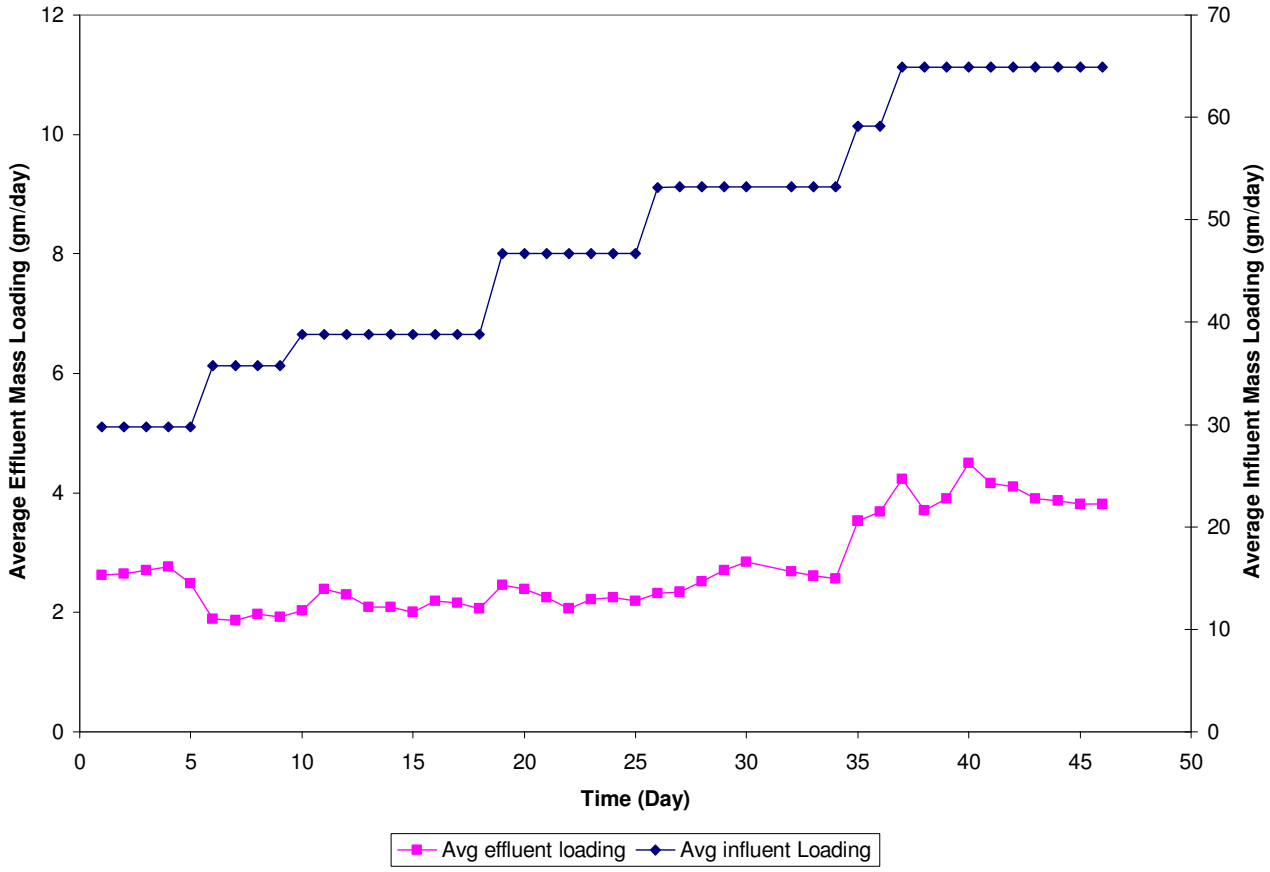

Figure 5.10: Variation of Average Influent and Effluent Organic mass loading at MLSS 3000 mg/L with Time

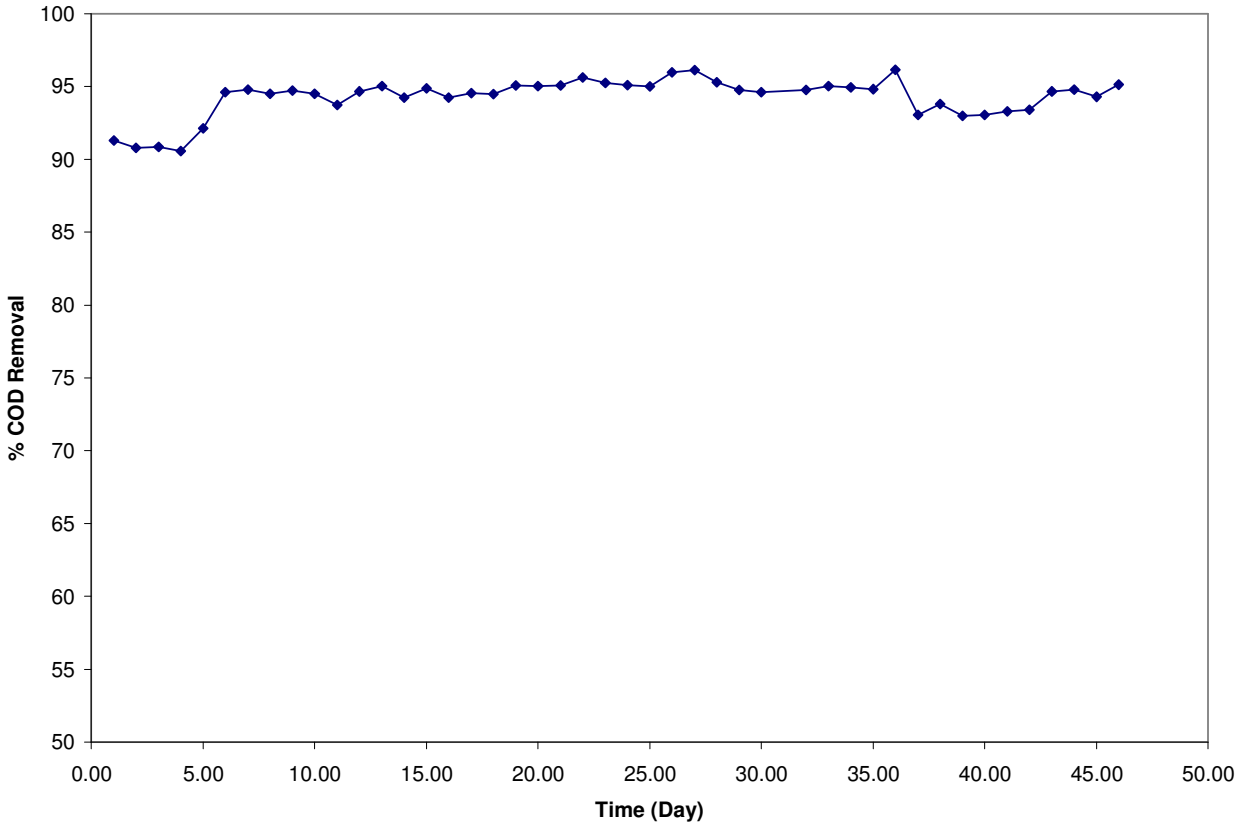

Figure 5.11: COD Removal Efficiency at MLSS 3000 mg/L with Time

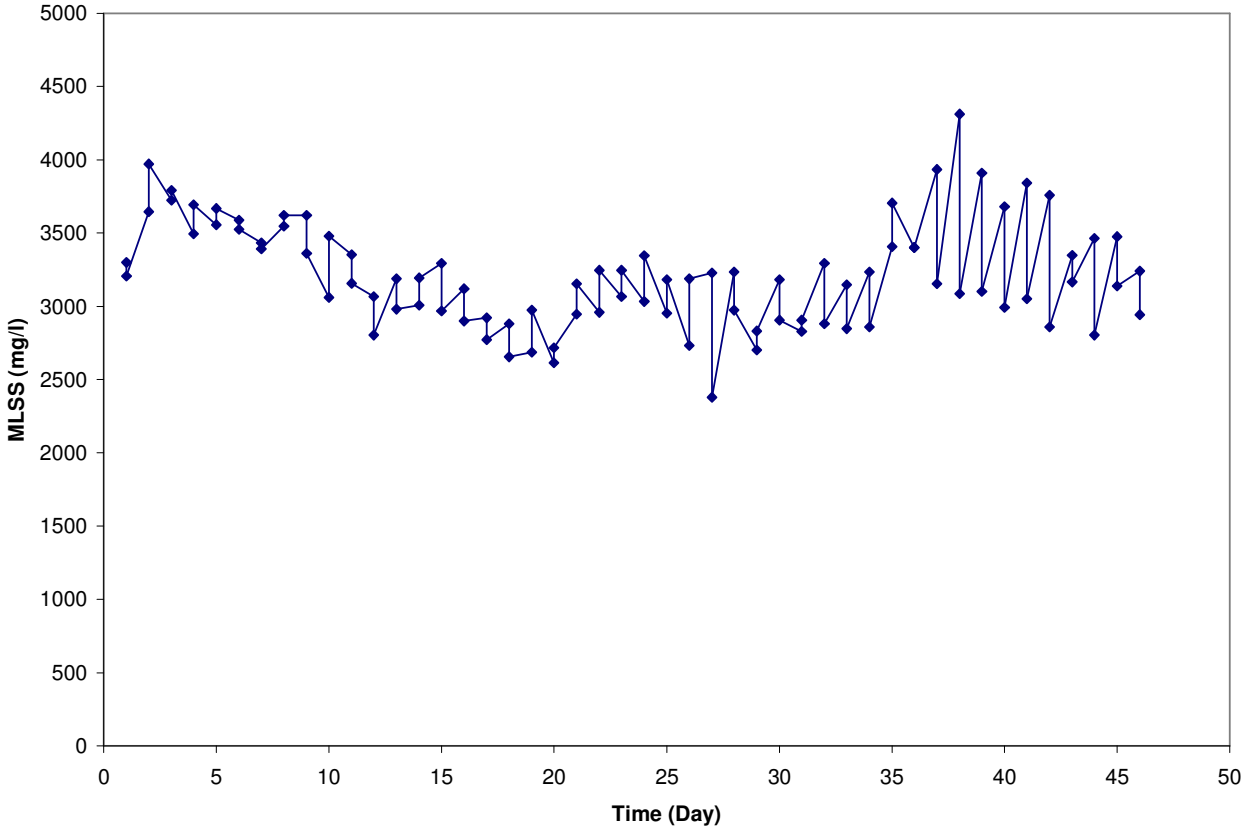

Figure 5.12: Variation of MLSS concentration with Time for MLSS 3000 mg/L

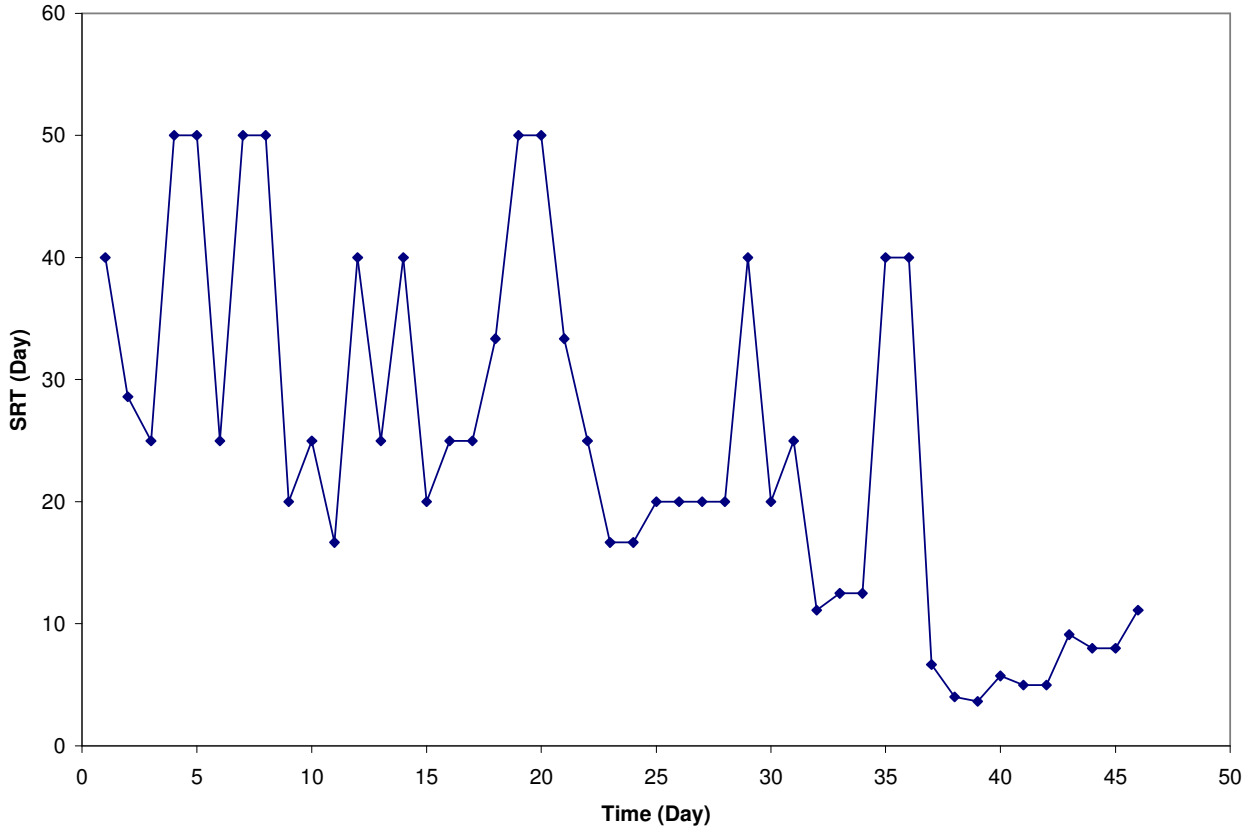

Figure 5.13: Variation of SRT with time at MLSS 3000 mg/l

5.1.4 Foam Control

As mentioned earlier that excessive foaming was encountered throughout the whole biokinetic study period, which caused loss of biomass from the reactor. This foaming was not due to over loading, because the DO was never less than 4 mg/l. According to El-kebir, 1991 this could be attributed to the release of surface active metabolic products which act like detergents. Attempts were made to prevent the foaming from carrying the biological solids out of the aeration tank. Breaking the rising bubbles manually was one of them but this was not possible to continue for 24 hrs. Any anti-foaming chemicals were not thought to be used because it might be detrimental to the biomass growth and also could increase the influent COD. However, complete control over foaming was achieved when compressed air flow was employed to break the bubbles. This technique was cheap and was able to prevent the formation of bubble continuously.

5.2 DETERMINATION OF BIOKINETIC COEFFICIENTS

5.2.1 Development of Kinetic model equation

Basic equations that describe the growth of microorganisms and utilization of the growth-limiting substrate in the activated sludge process are based on the Monod (1949) equations. The Monod model is still the most commonly and widely used model for the study of biokinetic coefficients. This model was accepted by the IAWPRC task group (Henze et al., 1987) as the fundamental basis for the development of activated sludge models.

Microorganisms require substrate for three main functions:

- To synthesize the new cell material
- To synthesize the extra-cellular products
- To provide the energy necessary to drive the reaction and maintain concentrations of materials within the cell which are different from those in the environment.

In both batch and continuous culture systems, the rate of growth of bacterial cells can be defined by the following relationship:

$$r_g = \mu X \qquad (5.1)$$

Where, r_g = rate of bacterial growth, mass/unit volume.time

μ = specific growth rate, $time^{-1}$

X = concentrations of microorganisms, mass/unit volume

For the batch culture, $dX/dt = r_g$; so the following equation is also valid for the batch reactor:

$$\frac{dX}{dt} = \mu X \qquad (5.2)$$

Where, t = time

The effect of a limiting substrate or nutrient can often be defined adequately using the following expression proposed by Monod (1949):

$$\mu = \mu_m \frac{S}{K_s + S} \tag{5.3}$$

where, μ_m = maximum specific growth rate, time^{-1}

S = concentration of growth limiting substrate surrounding the biomass, mass/unit volume

K_S = saturation constant which is numerically equal to the substrate concentration at $\mu = ½ \mu_m$, mass/unit volume.

Substituting the value of μ from equation 5.3 in equation 5.1, the resulting expression for the rate of growth is:

$$r_g = \frac{\mu_m XS}{K_s + S} \tag{5.4}$$

In batch and continuous growth culture systems, a portion of the substrate are converted to new cells and portion is oxidized to inorganic and organic end-products. The relationship between the mass of bacteria produced and the mass of organic substrate removed is quantified by a coefficient known as yield coefficient, Y, and numerically expressed as:

$$Y = \frac{dX / dt}{dS / dt} \tag{5.5}$$

The yield coefficient is usually assumed for a given biological process treating a specific waste. Yield also depends on

- Various physical parameters of cultivation

- The degree of polymerization of substrate
- Pathways of metabolism
- The growth rate and
- The oxidation state of the carbon source and nutrient elements.

The following relationship has been developed between the rate of substrate utilization and rate of growth:

$$r_g = -Yr_{su} \tag{5.6}$$

where, r_{su} = substrate utilization rate, mass/unit volume.time

In bacterial systems, used for the wastewater treatment, the distribution of cell ages is such that not all the cells in the system are in the log-growth phase. Consequently, the expression for the rate of growth must be corrected to account for the energy required for cell maintenance. Other factors, such as death and predation, must also be considered. Usually, these factors are lumped together and it is assumed that the decrease in cell mass caused by them is proportional to the concentration of organism present. This decrease is known as endogenous decay, $r_{d,}$ and it can be formulated as:

$$r_d = -k_d X \tag{5.7}$$

where, r_d = Endogenous decay, mass/unit volume.time

k_d = endogenous decay coefficient, $time^{-1}$

The growth of the biomass in the process can be expressed as:

$$\frac{dX}{dt} = \mu X - k_d X \tag{5.8}$$

Combining equations 5.1 and 5.5 gives

$$\frac{dS}{dt} = \mu \frac{X}{Y} \tag{5.9}$$

Rearranging equation 5.9 and substituting in equation 5.8 gives:

$$\frac{dX}{dt} = Y\frac{dS}{dt} - k_d X \tag{5.10}$$

Rearranging equation 5.10 gives:

$$\mu = UY - k_d \tag{5.11}$$

Where, U specific substrate utilization rate, time^{-1}, and is represented by:

$$U = \frac{Q(S_0 - S)}{VX} \tag{5.12}$$

Where, Q = flowrate, volume/time

S_0 = Influent substrate concentration mass/unit volume

S = Effluent substrate concentration mass/unit volume

The above equations (from 5.1 to 5.12) when combined, form the basis of the mathematical model for the crossflow membrane activated sludge in other words crossflow membrane bioreactor (CF-MBR) process.

Figure 5.14 shows the schematic diagram of the CF-MBR system. The model is developed with the following assumptions:

- The reactor is completely mixed (mixing was provided by means of stone aerator and recycling pump)
- The volume of the reactor is constant (the inflow is equal to the permeate flow); this was achieved by using a mechanical float.
- Complete rejection of MLSS (no biomass is allowed to come out with the permeate)
- Substrate is not rejected
- No microbial solids are contained in the influent substrate.

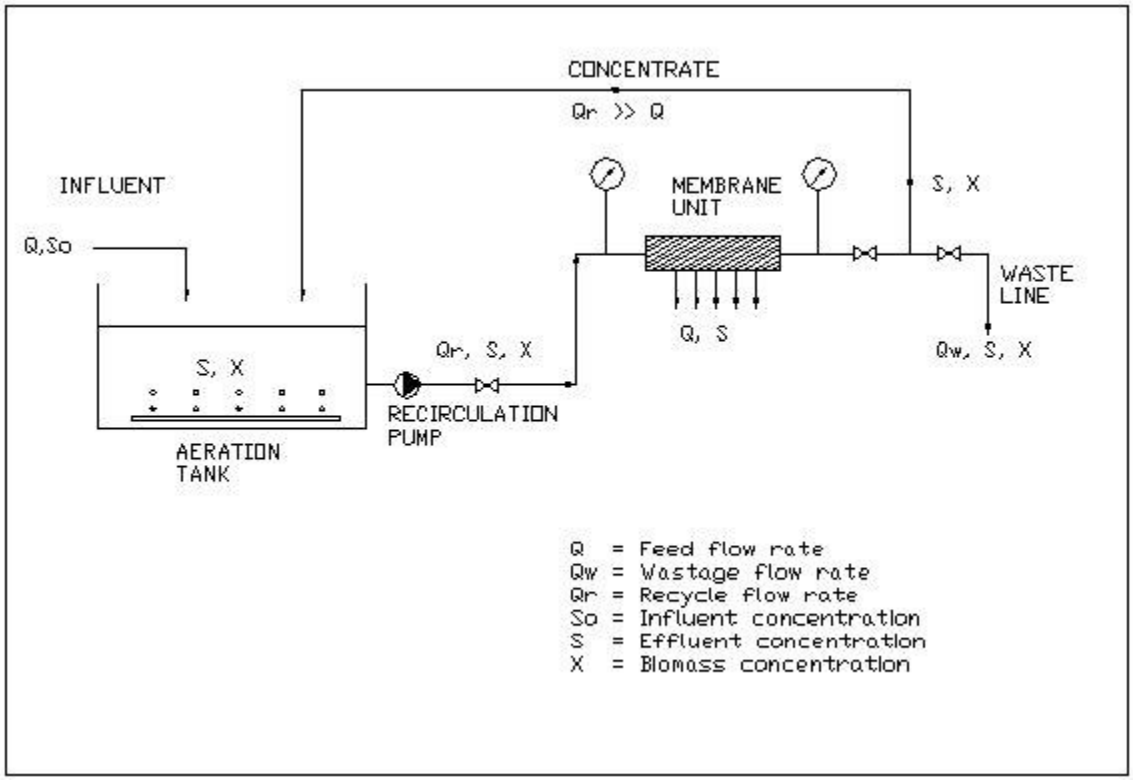

Figure 5.14: Complete mix CF-MBR system

The rate equations describing the performance of the system are the mass balance equations of both the biomass and substrate. These can be expressed as follows:

Biomass Balance

$$\begin{pmatrix}\text{Rate of change of}\\ \text{Biomass in the reactor}\end{pmatrix} = \begin{pmatrix}\text{Rate of increase}\\ \text{due to growth}\end{pmatrix} - \begin{pmatrix}\text{Rate of loss due to}\\ \text{endogenous respiration}\end{pmatrix} - \begin{pmatrix}\text{Deliberate}\\ \text{wastage}\end{pmatrix}$$

The symbolic representation of the above statement is:

$$V\frac{dX}{dt} = \mu XV - k_d XV - Q_w X \qquad (5.13)$$

Where, V =reactor volume, L

X = biomass concentration in the reactor, mg/l

μ = Specific growth rate, day^{-1}

Q_w = wastage flow rate, l/day

For steady state condition, dX/dt = 0,

Hence, equation 5.13 can be expressed as:

$$\mu = k_d + \frac{Q_w}{V} \qquad (5.14)$$

Since the solid retention time (SRT) is defined as:

$$SRT = \frac{Total\ mass\ of\ organisms\ in\ the\ reactor}{Total\ mass\ of\ organisms\ leaving\ the\ system\ per\ day}$$

then,

$$SRT = \frac{VX}{Q_w X} = \frac{V}{Q_w} \qquad (5.15)$$

Substituting equation 5.15 in equation 5.14, gives:

$$\mu = k_d + \frac{1}{SRT} \tag{5.16}$$

Substituting equation 5.3 in equation 5.16 yields the steady state for substrate concentration in the reactor:

$$S = \frac{K_s\left(\frac{1}{SRT} + k_d\right)}{\mu_m - \left(\frac{1}{SRT} + k_d\right)} \tag{5.17}$$

Substrate Balance

(The rate of Change of Substrate in The reactor) = (Rate of input of the feed substrate) - (Rate of removal due to biomass utilization) - (Rate of removal due to washout) - (Substrate lost during deliberate wastage of biomass)

The mathematical representation of the above statement can be written as:

$$V\frac{dS}{dt} = QS_0 - \mu\frac{XV}{Y} - S(Q - Q_w) - Q_w S \tag{5.18}$$

At steady state, dS/dt = 0,

Therefore, equation (5.18) can be rewritten as:

$$\frac{Q}{V}(S_0 - S) = \mu\frac{X}{Y} \tag{5.19}$$

Substituting equation 5.16 into equation 5.19 gives the biomass concentration at steady state condition:

$$X = Y\frac{Q}{V}\frac{(S_0 - S)}{k_d + \frac{1}{SRT}} \tag{5.20}$$

5.2.2 Determination of Kinetic Coefficients

The purpose of studying the kinetic coefficients was to obtain information on the rate of cell growth and consumption of substrate. This enabled the required volume of the reactor to be calculated and simulation of the system can be used for process control. The kinetic coefficients of a biological system have generally been determined experimentally using either completely mixed continuous flow or batch lab-scale reactors.

In continuous-flow complete-mixed reactor, the determination of the kinetic coefficients is usually achieved by collecting data from lab-scale or pilot-plant experiments. Operating the system at various hydraulic retention times (HRT) and/or at various sludge retention times (SRT) and by allowing (at each adapted stage of HRT or SRT), a steady state condition to prevail. Accurate measurements of the biomass and permeate substrate concentration are then recorded. The kinetic coefficients such as K_s,μ,Y and k_d can be determined through linearization of equations 5.17 and 5.20. To determine the kinetic coefficients, k_d and Y, rearranging equation 5.20 gives

$$\frac{Q}{VX}(S_0 - S) = \frac{1}{Y}\frac{1}{SRT} + \frac{k_d}{Y} \tag{5.21}$$

To determine the kinetic coefficients, μ_m and K_s, rearranging equation 5.17 gives

$$\frac{SRT}{1 + (SRTk_d)} = \frac{K_s}{\mu_m}\left(\frac{1}{S}\right) + \frac{1}{\mu_m} \tag{5.22}$$

If equation 5.21 is plotted as $\frac{Q}{VX}(S_0 - S)$ versus *1/SRT*, then from the slope and the Y-intercept, it is possible to determine the kinetic coefficients Y and k_d. Substituting the obtained value of k_d in equation 5.22 and plotting $\frac{SRT}{1+(SRTk_d)}$ versus *1/S*, then from the slope and the Y-intercept it is possible to determine the kinetic coefficients K_s and μ_m.

The biokinetic coefficients studies in the CF-MBR unit were carried out in a similar fashion outlined beforehand. In the study period SRT was used as a parameter to control the growth rate of the biomass instead of HRT. This was achieved by running the unit at various organic mass loading and also by wasting various volumes of biomass from the system.

The concentration of the MLSS of the bioreactor was kept constant by wasting the biomass once and occasionally twice a day. Sometimes it was found from MLSS measurement after wasting that the value of MLSS was more than before wasting. It might happen either because of erroneous sample collection due to the non uniform mixing of the biomass in the reactor or the rapid increase in biomass. So the MLSS was wasted for the second time to keep the MLSS concentration constant. A steady-state condition was assumed to be achieved when fairly constant biomass growth and filtrate COD were attained and was within standard deviation of 5% (Diez et.al., 2002).

The kinetic study was initiated with a biomass concentration of 5000 mg/l. Because of the long acclimatization period to the oil and glucose based nutrient, the first steady state condition was achieved after only eighteen days from the start of the unit operation. The steady state was maintained for five days, after which it was decided to increase the organic mass loading from 41.110 gm/day to 45.469 gm/day. At this point it was

observed interestingly that increasing the mass loading did not increase the effluent COD significantly. When the effluent COD variation was found within the chosen standard deviation (5%) for four days, the duration was considered as the second steady state condition. To get the third and fourth steady state point, the mass loading was increased up to 57.861 gm/day and 64.693 gm/day, respectively, and the steady state conditions were prevailed for four days. The maximum COD removal efficiency at MLSS 5000 mg/l was achieved during the fourth steady state period which was 96.71 %.

Table 5.1 shows the steady state data for MLSS concentration of 5000 mg/l. A linear regression was used on these points in accordance with equations (5.21) and (5.22). The plots are shown in figure 5.15 and 5.16, respectively, which were used to determine the kinetic coefficients summarized in Table 5.3.

During the kinetic coefficients study period at MLSS 3000 mg/l, various mass loading were applied and various steady state points were obtained accordingly. The loading was varied from 35.775 to 62.545 gm/day to attain four steady state points. All the four steady state conditions were maintained for four days except the third point. The COD removal efficiency was in the range of 90 to 97% with a maximum of 96%.

The results of the steady state conditions are shown in Table 5.2. Figures 5.17 and 5.18 are plotted with the help of Table 5.2 for the determination of kinetic coefficients. The coefficients are shown in Table 5.3.

Table 5.1: Steady state data at MLSS 5000 mg/l

Steady State Period	Q	X_{avg}	S	1/S	QS_0	QS	SRT	$Q(S_0-S)/VX$	$SRT/(1+SRT*k_d)$
day	l/day	mg/l	mg/l	l/mg	gm/day	gm/day	day	1/day	day
18- 22	38	5458	72.00	0.0139	41.110	2.741	30.00	0.35	9.68
23-26	36	5300	84.00	0.0119	45.469	3.003	25.42	0.40	9.15
38-41	33	5393	109.00	0.0092	57.861	3.590	15.30	0.50	7.39
48 -51	19	5511	120.00	0.0083	64.693	2.281	11.00	0.57	6.21

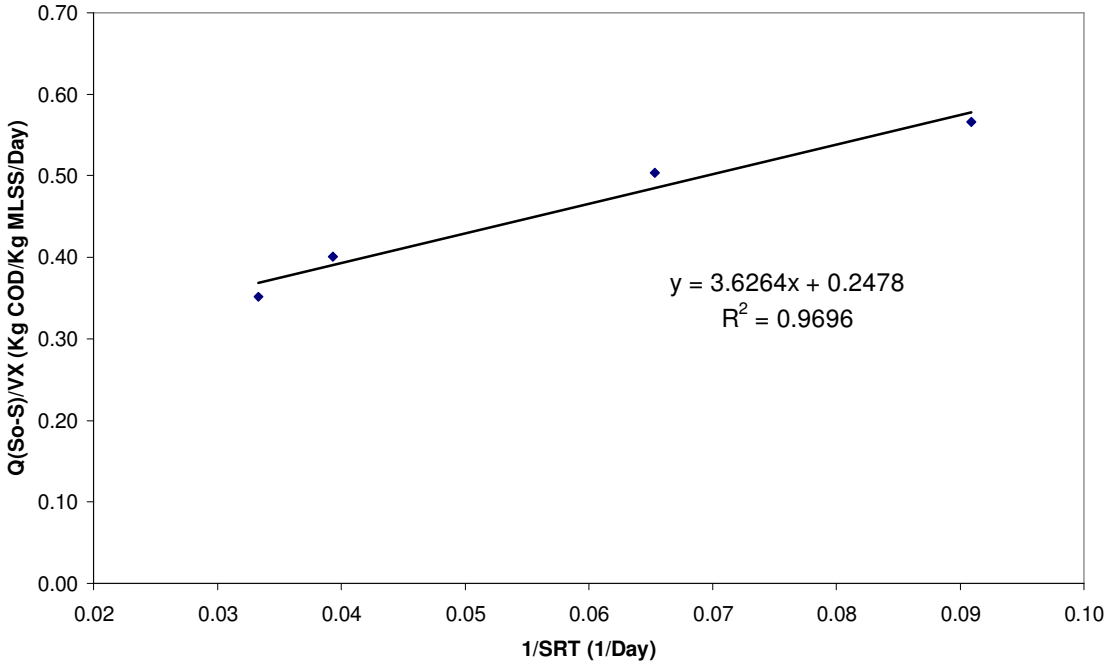

Figure 5.15: Determination of Y and k_d at MLSS 5000 mg/l

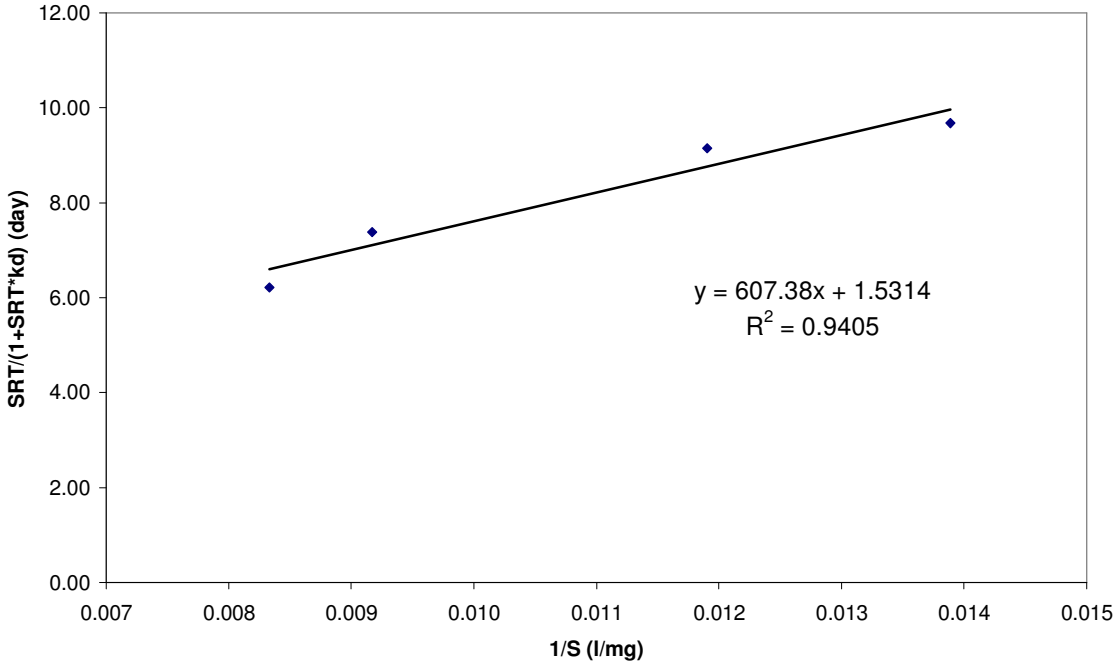

Figure 5.16: Determination of μ_m and K_S at MLSS 5000 mg/l

Table 5.2: Steady state data at MLSS 3000 mg/l

Steady State Period	Q	X_{avg}	S	1/S	QS_0	QS	SRT	$Q(S_0-S)/VX$	$SRT/(1+SRT*k_d)$
day	l/day	mg/l	mg/l	l/mg	gm/day	gm/day	day	1/day	day
6 -9	27	3547	70	0.0143	35.775	1.918	36.25	0.48	8.5
22-25	22	3184	101	0.0099	46.966	2.241	19.58	0.70	7.09
32-34	25	3224	110	0.0091	53.775	2.724	12.04	0.79	5.78
43-46	28	3382	116	0.0086	62.545	3.292	9.05	0.88	4.99

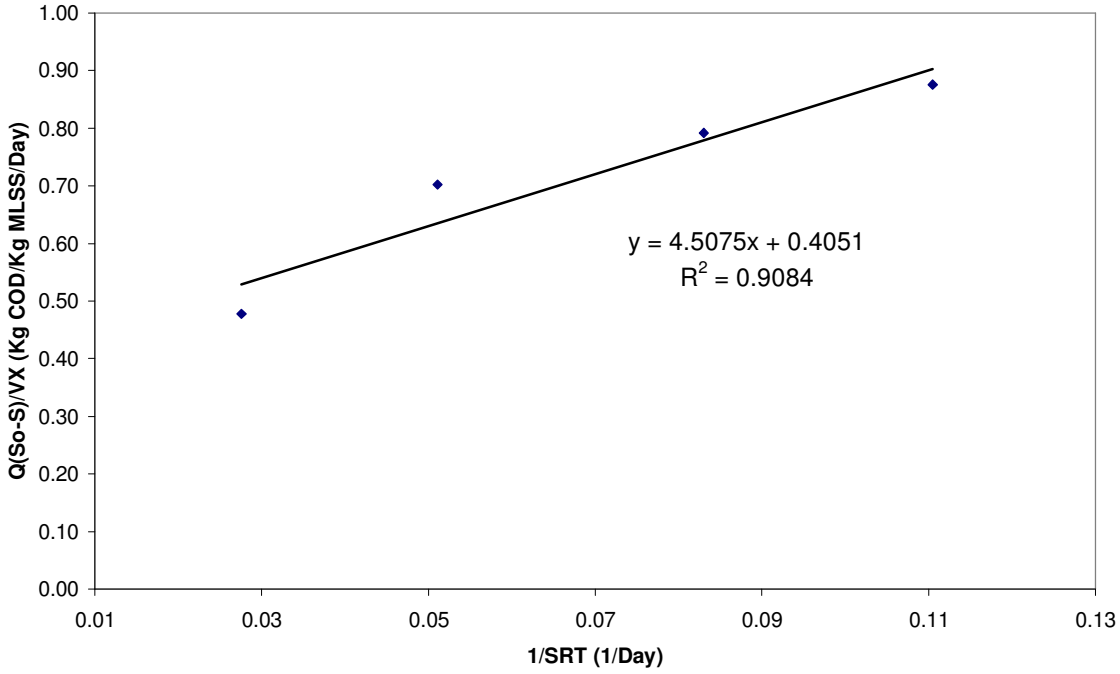

Figure 5.17: Determination of Y and k_d at MLSS 3000 mg/l

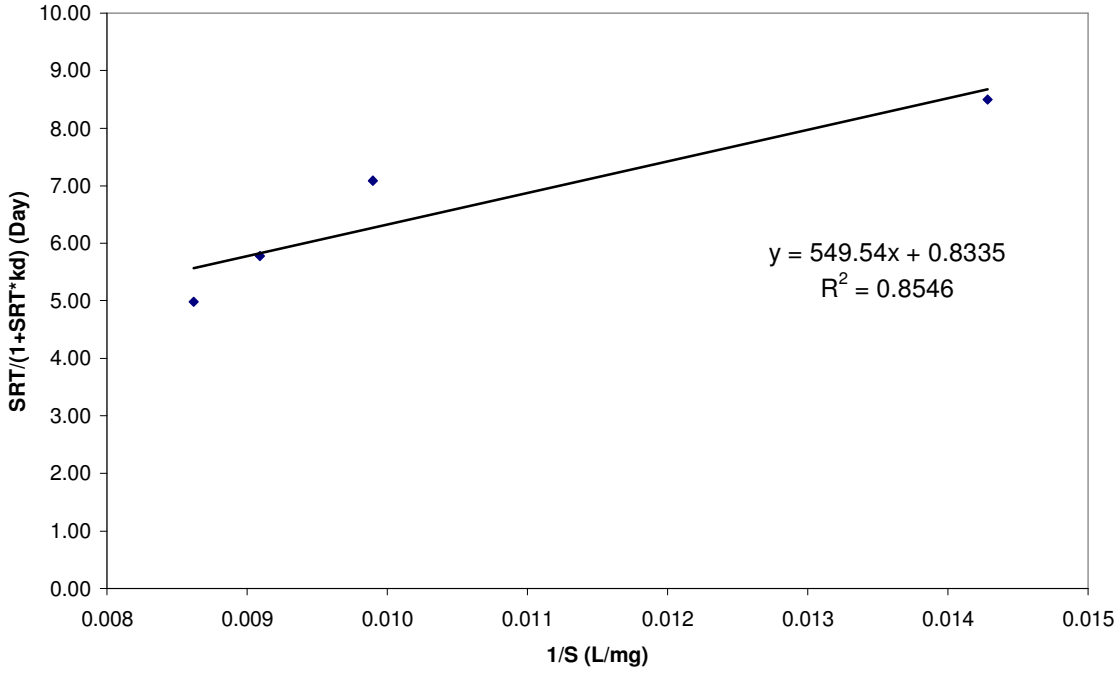

Figure 5.18: Determination of μ_m and K_S at MLSS 3000 mg/l

Table 5.3: Kinetic Coefficients for CF-MBR at different MLSS concentrations

MLSS, mg/l	Y (mg/mg)	K_d (day^{-1})	μ_m (day^{-1})	K_S (mg COD/l)
5000	0.276	0.07	0.653	396.62
3000	0.222	0.09	1.2	659.45

It is apparent from the table that the coefficients change with the change of MLSS concentrations. Off course this variability does not follow any particular pattern to draw a straight-forward conclusion. This variability might be attributed to the character of the system itself, as the system could be a selective process and kinetic coefficient obtained might represent different species (Kalyandurg, 2003). This is supported by the investigation of the performance of the unit during the study period. For an instance, when the period was running at MLSS 3000 mg/l, after the operation of five days when the organic mass loading increased, the effluent COD decreased, which was supposed to be increased at the increased mass loading. The same occurrence happened at MLSS 5000 mg/l also. The reasons behind this phenomenon might be as follows:

- Since the growth rate was controlled by the SRT which was carried out daily by wasting a certain amount of MLSS, this might have affected the growth kinetics of the microbial population in the system. The continuous culture process is a competitive process, which results in the enrichment of a bacterial species at a particular SRT, i.e. species with higher values of specific growth rate (μ) appeared to be predominant at lower SRT while those species having lower value of μ were enriched in the system only at high SRT (El-Kebir, 1991).
- Due to harsh conditions imposed on the populations in the system (shear and pressure). The system could have contributed towards selecting species that can be stand, grow and survive the applied conditions.

Generally, the values of kinetic coefficients presented in Table 5.3 are within the normal range of the activated sludge process found in the literature, except the values of Y. The reason behind the relatively low value of Y might lead to the oxidation state of the carbon

source and nutrient elements (Metcalf & Eddy, 1991). Table 5.4 summarizes some of the kinetic coefficients obtained from different sources. Although, k_d, μ_m and K_S are within the reported values, they also differ quite significantly. The Y values were increasing with the increase of MLSS concentrations as they represent all the amount of biomass produced by the growth during the removal of substrate.

The decay rate k_d, as listed in Table 5.3, shows an increase as the MLSS concentrations decreases. This probably is a result of the harsh condition (shear and pressure) which biomass was subjected to. These effects appear more pronounced at low concentrations because the likelihood of the biomass cells being subjected to physical stress is higher at lower concentration.

5.2.3 Simulation of steady state condition

As stated in Section 5.2.2, the derivation of Equation 5.17 was based on the assumption that the CF-MBR unit was running under the steady state conditions. However, to test the validity of equation 5.17 in predicting the effluent COD at various SRT, a simulation was carried out using Equation 5.17. The kinetic parameters summarized in Table 5.3 were used in the simulation results of the model. Figure 5.19 shows the level of effluent COD at the variation of SRT for different MLSS concentrations.

Table 5.4: Some of typical values of the kinetic coefficients for aerobic bacteria

Substrate	Basis of analysis	Y (mg/mg)	k_d (day^{-1})	μ_m (day^{-1})	K_s (mg /l)	Treatment system	Reference
Municipal waste	COD	0.5-0.62	0.025-0.48	7.4-18.5	11-181	ASP	Gaudy & Gaudy, 1980
Municipal waste	COD	0.4-0.8	0.025-0.075	2-10	15-70	ASP	Metcalf & Eddy, 1991
Municipal waste	COD	0.48-0.6	0.05-0.16	5.6-8.10	250-3720	CF-ASP	El-Kebir, 1991
Synthetic waste	COD	0.49-0.58	0.03-0.15	1.28-6.46	289-2933	SM-ASP	Kaly andurg, 2003
Industrial waste	COD	0.3-0.72	0.045	0.77	2980.5	ASP	Suman Raj, 2004
Oily waste	COD	0.22-0.28	0.07-0.09	0.65-1.2	397-660	CF-ASP	This Study

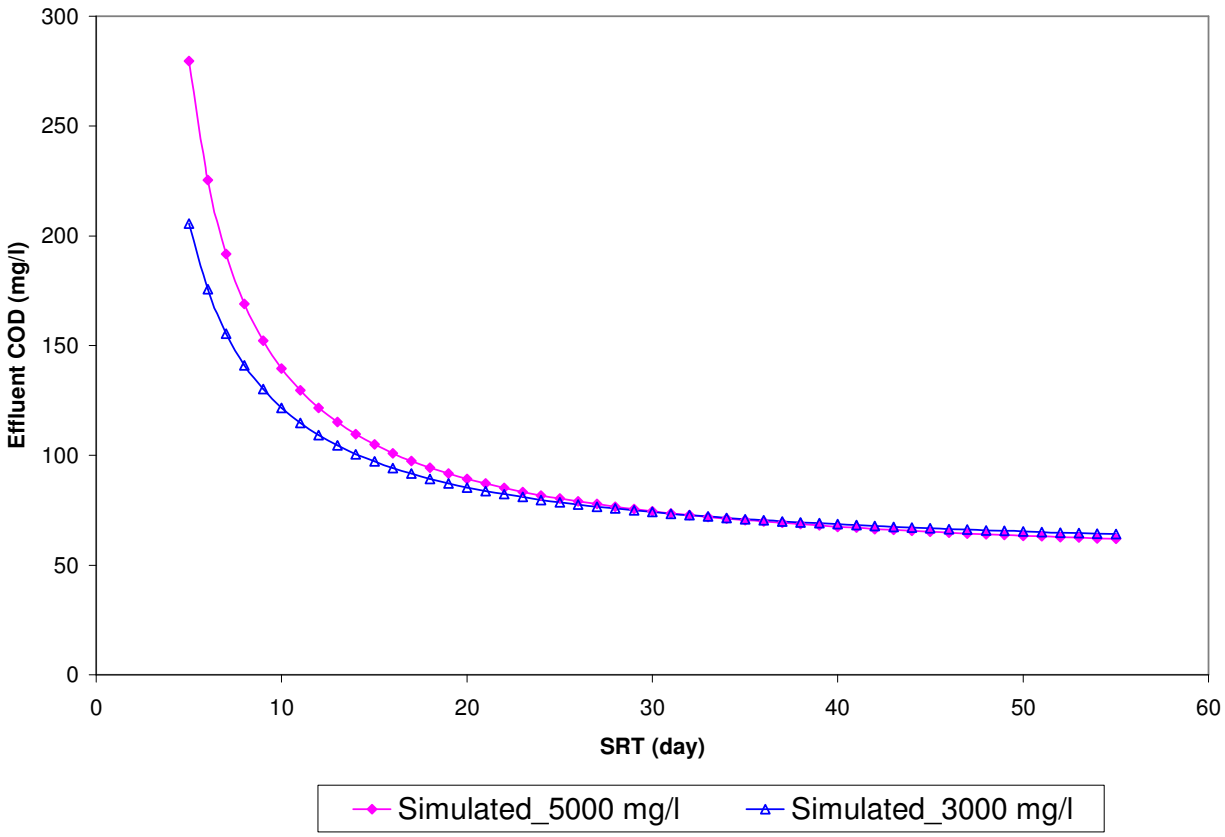

Figure 5.19: Experimental and Simulated Effluent COD for Different MLSS concentrations

Plotting both the simulated curves for different MLSS concentration on the same graph provides an assessment of how the performance of the unit can be described by the Monod model. It is clear from the simulated curves that up to a certain point, as the SRT increased, effluent COD decreased; after this the SRT had no effect on the effluent COD concentrations. Also, as the MLSS concentrations in the aeration tank increased, the Effluent COD increased. This phenomenon might result from the accumulation of end-products (El-kebir, 1991), which contain a wide variety of high and low molecular weight compounds, including humic and fulvic acids, organic acids, amino acids, antibiotics, enzymes, structural components of cells and products of metabolism.

5.3 EFFECT OF HRT ON THE PERFORMANCE OF CF-MBR PROCESS

The effect of hydraulic retention time (HRT) on the performance of CF-MBR cannot be ignored. In the determination of the kinetic coefficients, solid retention time (SRT) was the controlling parameter, but neither the flux nor the HRT were controlled in that part of the study. Hence experiments were carried out to see the effect of variation of HRT on the system performance in terms of flux stability and COD removal efficiency at different MLSS concentration. These experiments were conducted at three HRT conditions. After finishing each experiment at a selected HRT, the membranes were cleaned to restore the flux and the investigation was conducted at the next selected HRT. The flow of biomass passed to membrane unit was measured by flow meter as well as manual measurement to calculate the crossflow velocity (CFV). However, change in CFV eventually symbolizes the change in HRT and in the presentation of the results of the current study, CFV has been chosen as the parameter for the purpose of comparison.

The experiment began with the MLSS concentration of 5000 mg/l. Figure 5.20 represents the flux variation with time at MLSS concentration of 5000 mg/l at different CFV. It can be seen at higher CFV of 3.24 m/s and 2.69 m/s that initially the flux increased for some time and then started decreasing. This increase is due to the fact that the pump was not operated at full flow at the beginning of the study because of the formation of cavity inside the pump. With the passage of time, the cavities disappeared and pump flow improved. More flux fluctuation at higher CFV is evident in the figure.

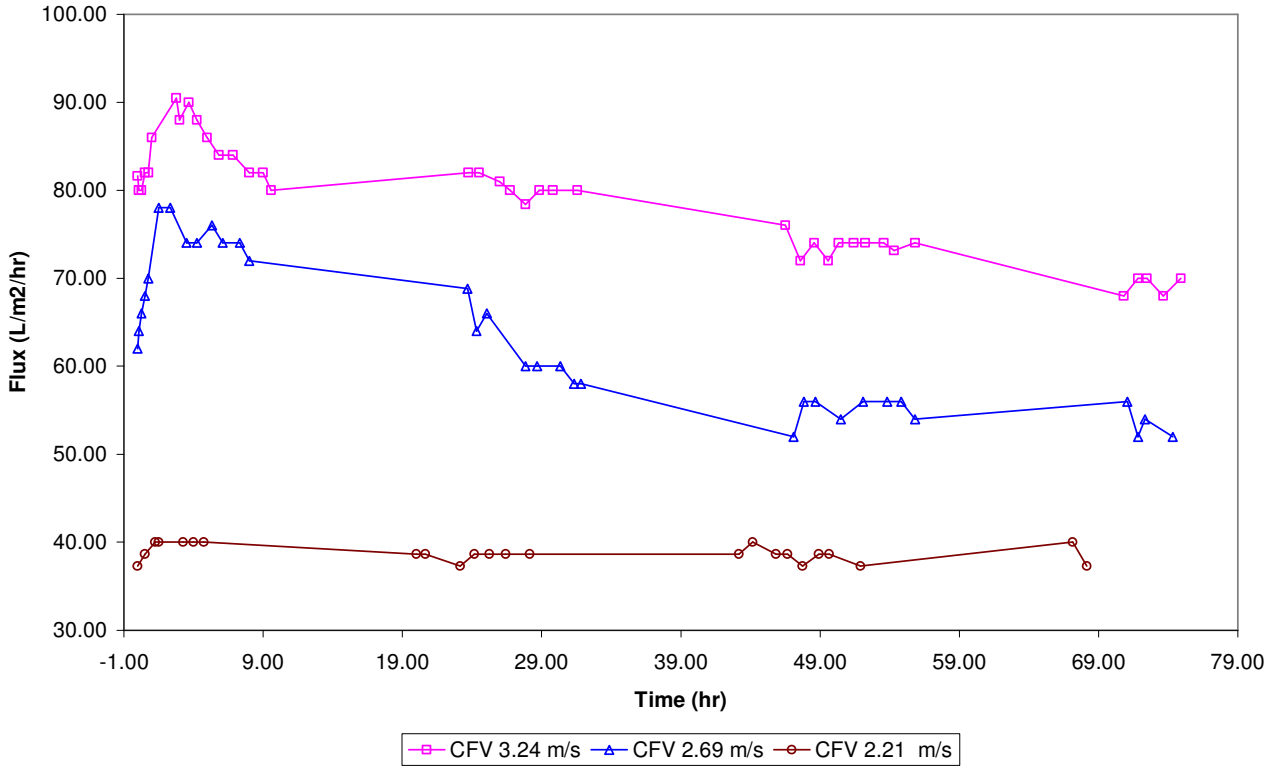

Figure 5.20: Variation of Flux with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

The experiment with CFV 2.21 m/s was started without cleaning the membrane. As the membranes are previously fouled, less fluctuation in flux is observed which might be already in steady state condition. On an average the flux was 79, 63 and 39 $L/m^2/hr$ at CFV of 3.24, 2.69 and 2.21 m/s respectively. Figure 5.21 represents the variation of TMP with time. The average TMP was 10, 6.5 and 4 psi at CFV of 3.24, 2.69 and 2.21 m/s respectively. The HRT varied (Figure 5.22) with an average of 17, 22 and 34 hr at CFV of 3.24, 2.69 and 2.21 m/s, respectively, at an MLSS concentration of 5000 mg/l.

To find the COD removal performance of the system, various organic mass loading was applied under different CFV. Obviously the influent and effluent mass loading decreased with the decreasing CFV and in other words with increasing HRT. The influent and effluent mass loading trends are shown in Figure 5.23 and Figure 5.24. The system was put in with an average influent mass loading of 43, 41 and 36 gm/day and resulted the effluent mass loading of 2.66, 2.45 and 1.71 gm/day at the CFV of 3.24, 2.69 and 2.21 m/s, respectively.

Figure 5.25 represents the COD removal efficiency for different CFV at MLSS of 5000 mg/l. Although the highest removal efficiency (95%) is observed at HRT of 34 hr and CFV of 2.21 m/s, yet the removal efficiencies at HRT of 22 hr (CFV 2.69 m/s) and 17 hr (CFV 3.24 m/s) are very close (94%) to this value. From the result it can be postulated that HRT did not affect the system in COD removal efficiency which varied in a narrow range of 93%-95%.

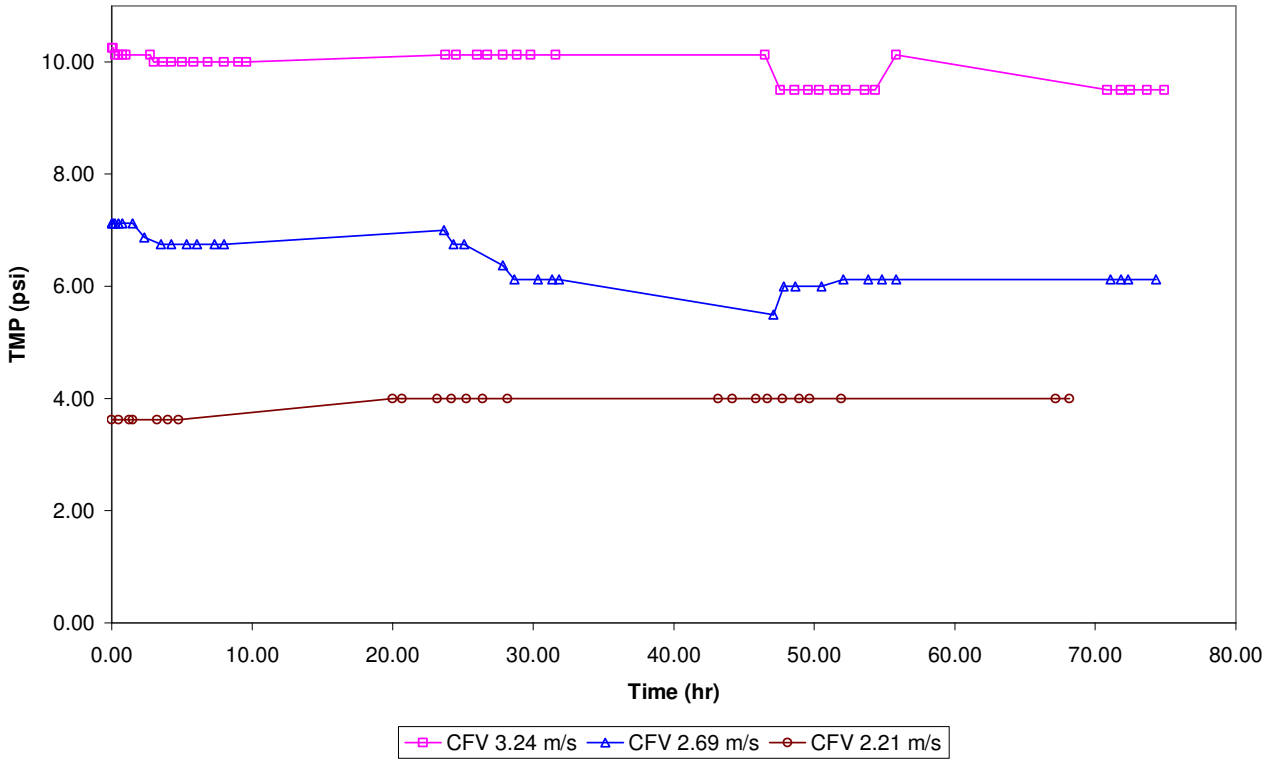

Figure 5.21: Variation of Transmembrane Pressure (TMP) with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

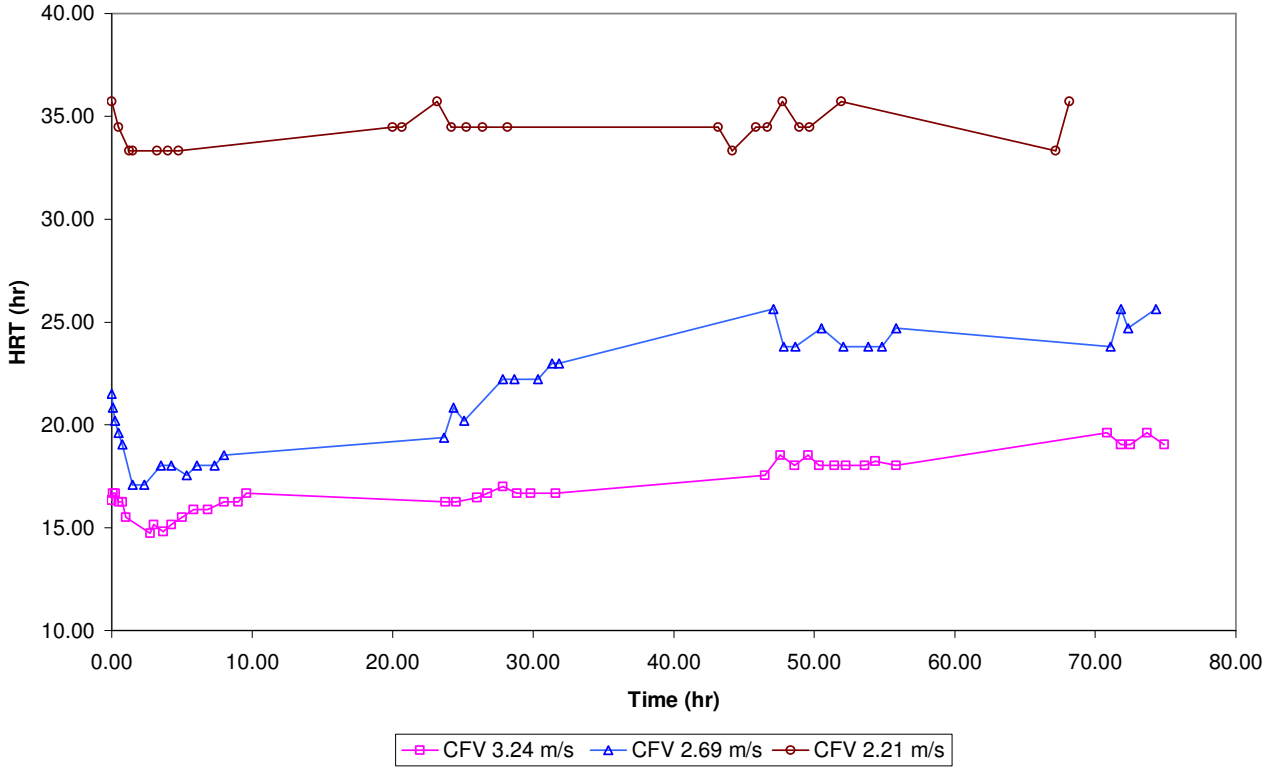

Figure 5.22: Variation of Hydraulic Retention Time (HRT) with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

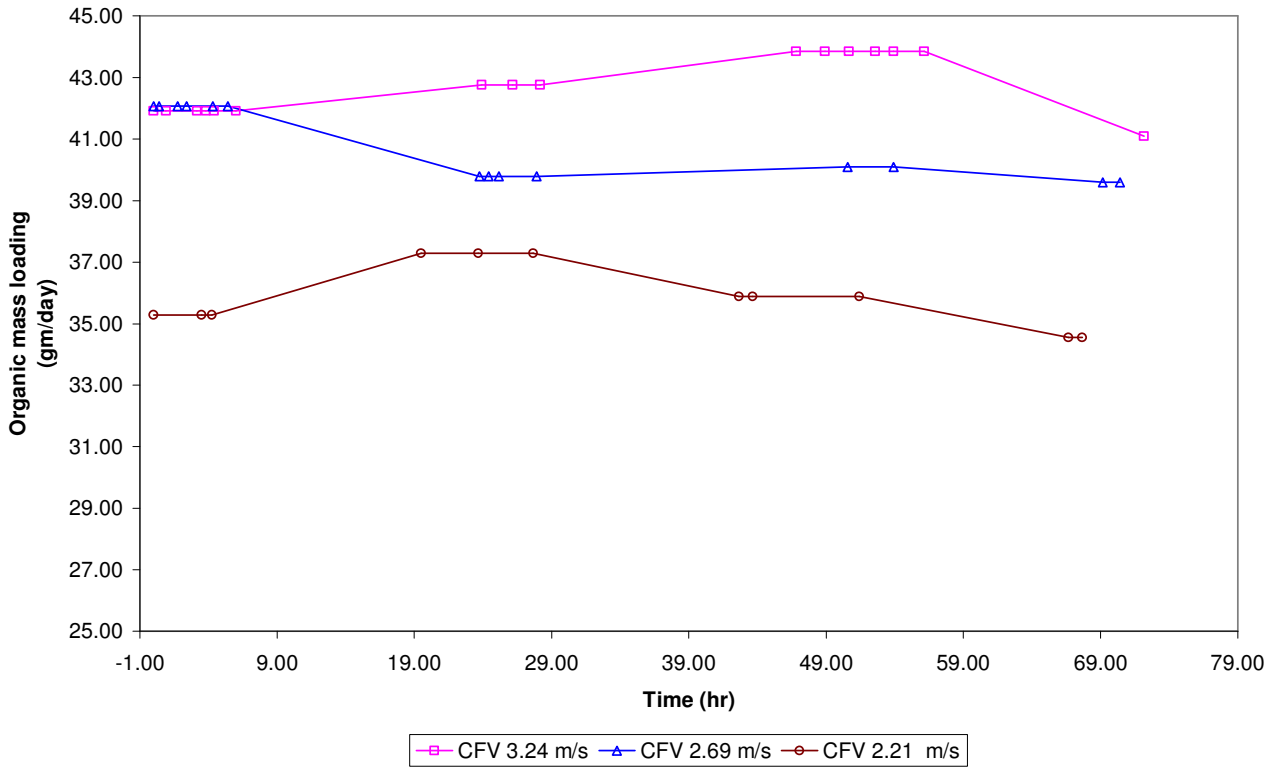

Figure 5.23: Variation of average influent Organic mass Loading with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

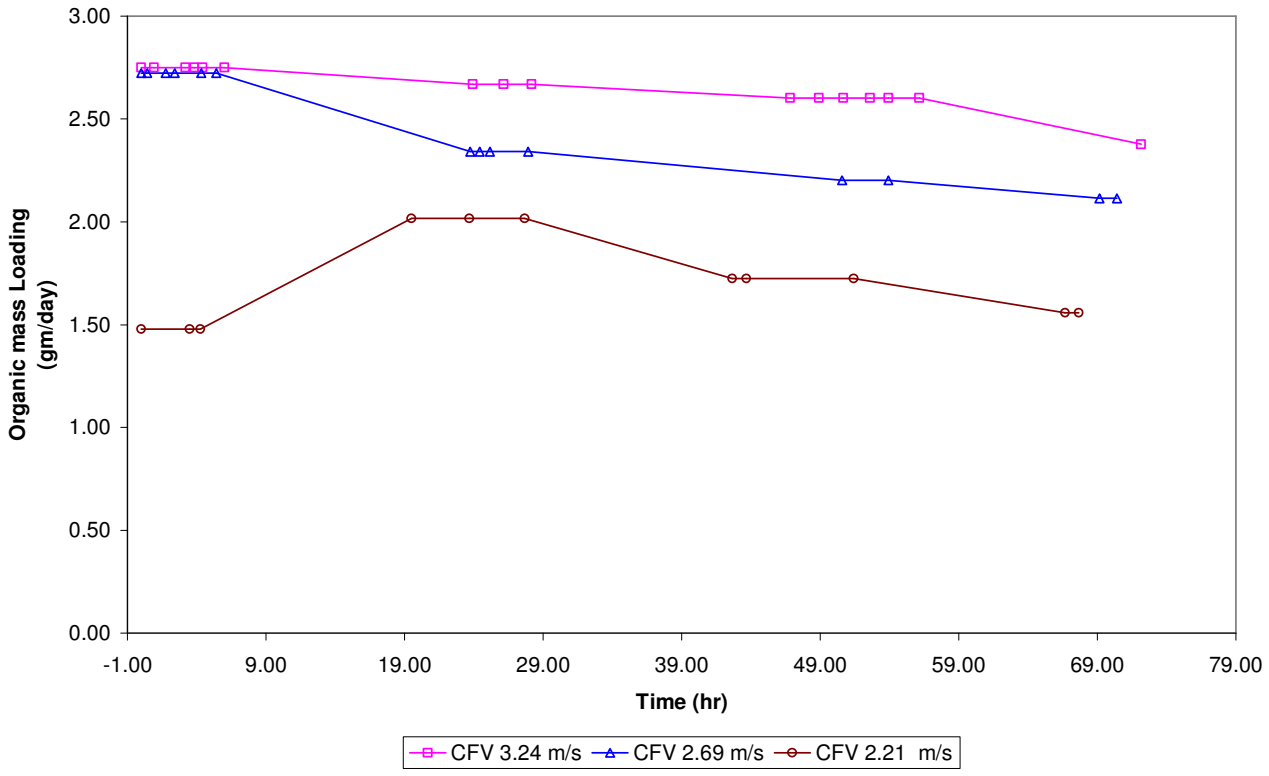

Figure 5.24: Variation of average Effluent Organic Mass Loading with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

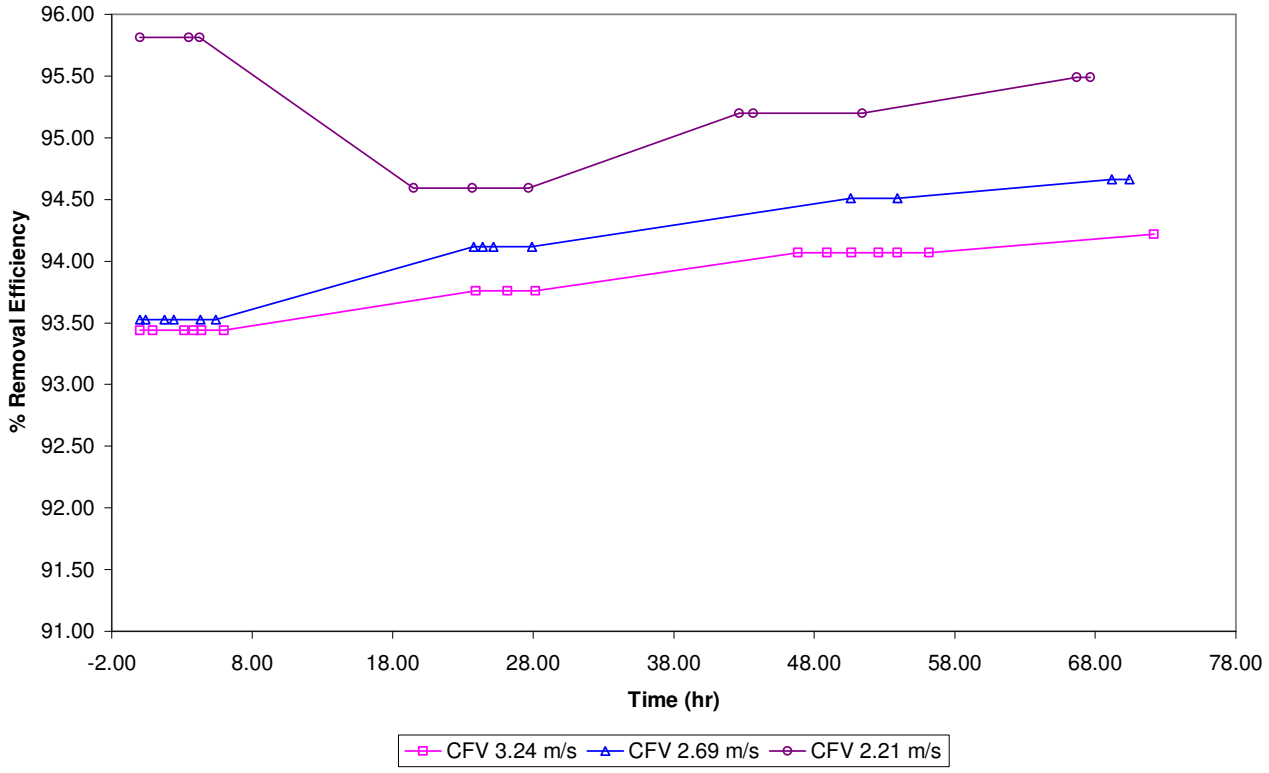

Figure 5.25: Variation of COD Removal Efficiency with time for different Crossflow Velocity (CFV) at MLSS of 5000 mg/L

After finishing the experiment at MLSS 5000 mg/l, the biomass was wasted to maintain the MLSS concentration at 3000 mg/l. At this MLSS concentration, the same procedure was applied for maintaining three different HRT conditions by controlling the CFV. Effort was given to keep the CFV values same as adopted for the experimental run at MLSS of 5000 mg/l to make the results comparable.

Figures 5.26 to 5.28 represent the trend of flux, TMP and HRT, respectively, during the experimental run at MLSS of 3000 mg/l. On an average the flux was 85, 68 and 41 $L/m^2/hr$, the TMP 10, 6.8 and 3.6 psi and the HRT 16, 20 and 33 hr at CFV of 3.39, 2.76 and 2.25 m/s respectively. In this MLSS concentration also various organic mass loadings were applied under different CFV. The influent and effluent mass loading trends are shown in Figures 5.29 and 5.30. The system was fed with an average influent mass loading of 43, 40 and 36 gm/day and resulted the effluent mass loading of 2.61, 2.26 and 1.84 gm/day at the CFV of 3.39, 2.76 and 2.25 m/s, respectively.

Figure 5.31 shows the COD removal efficiency for different CFV at MLSS of 3000 mg/l. As in the case of MLSS concentration of 5000 mg/l, the highest removal efficiency (95%) was observed at highest HRT of 33 hr and at lowest CFV of 2.25 m/s. The removal efficiency at rest of the HRT values remained same as previous (94%). It can be observed that COD Removal efficiency is independent of HRT at different MLSS concentration. This might happen because of the reason that the adopted HRTs are close to each other to demonstrate the variation in COD removal efficiency and the experiments ran for a short duration of time to allow sufficient time span to degrade the high molecular weight compound derived from the oily waste.

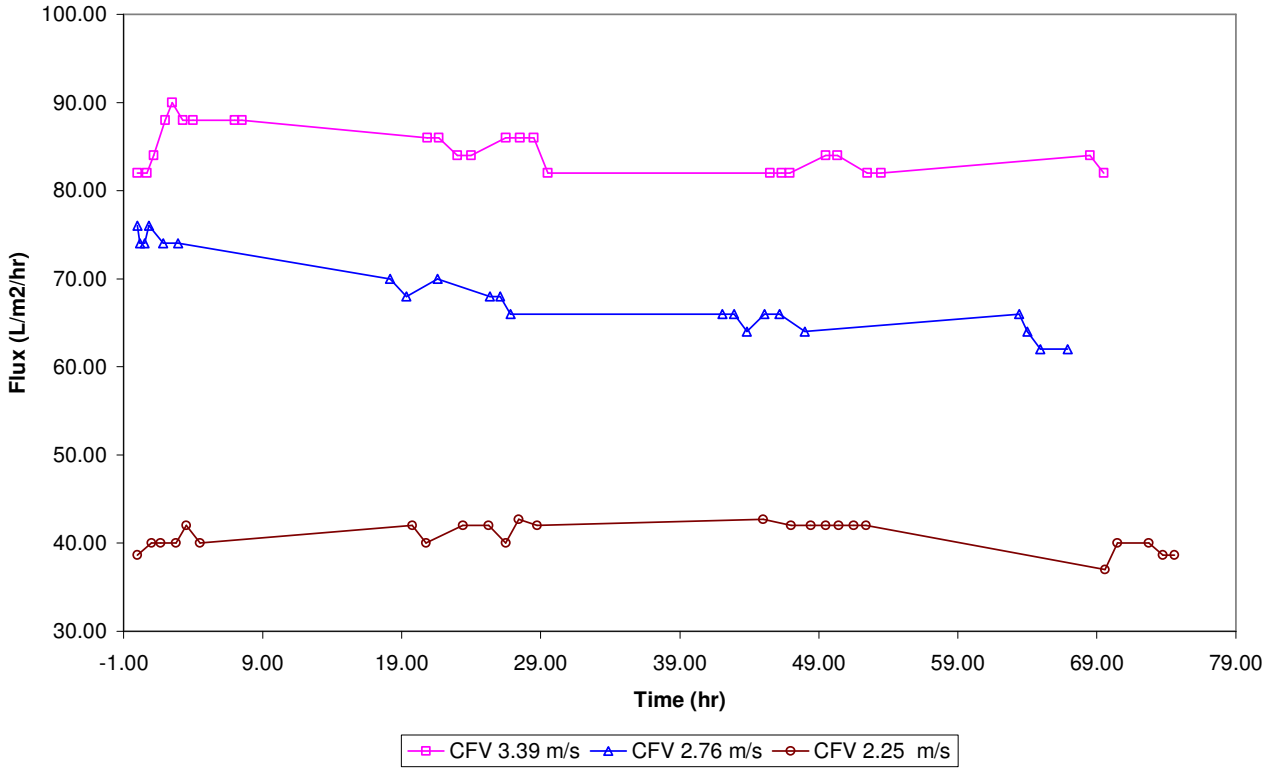

Figure 5.26: Variation of Flux with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

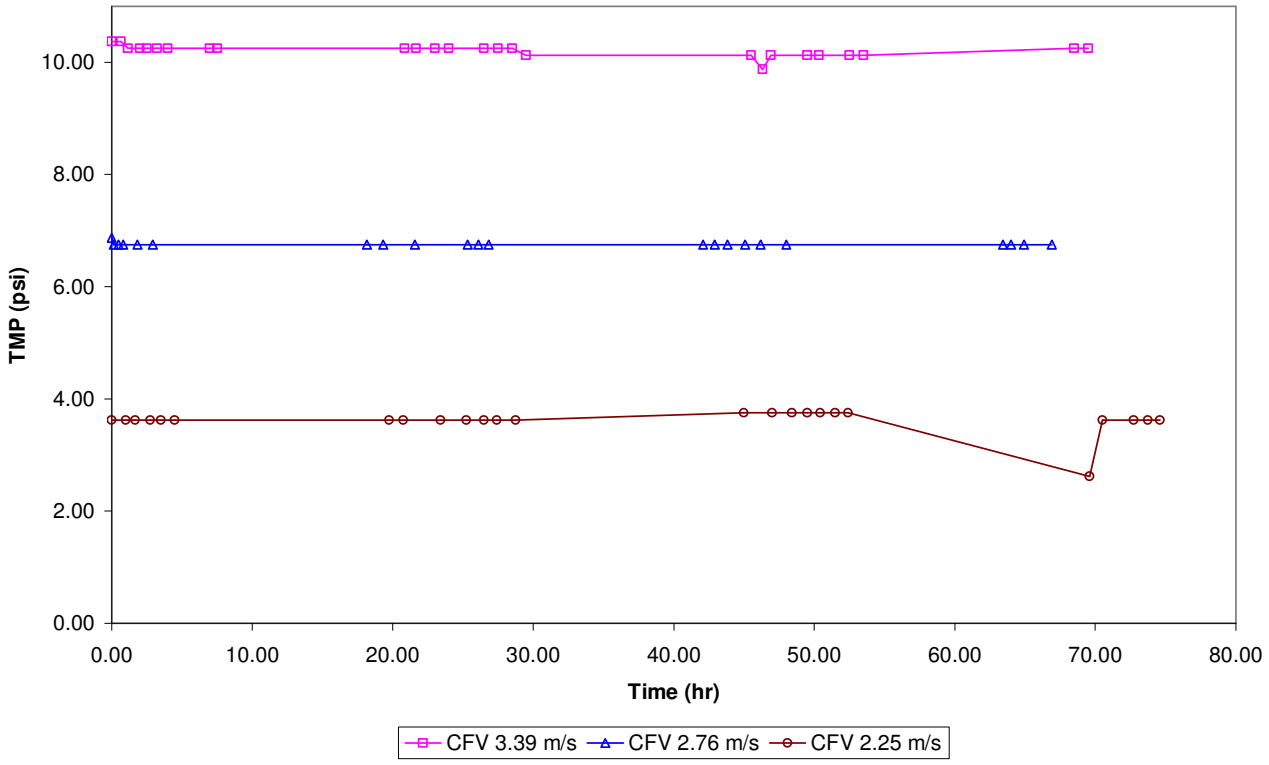

Figure 5.27: Variation of Transmembrane Pressure (TMP) with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

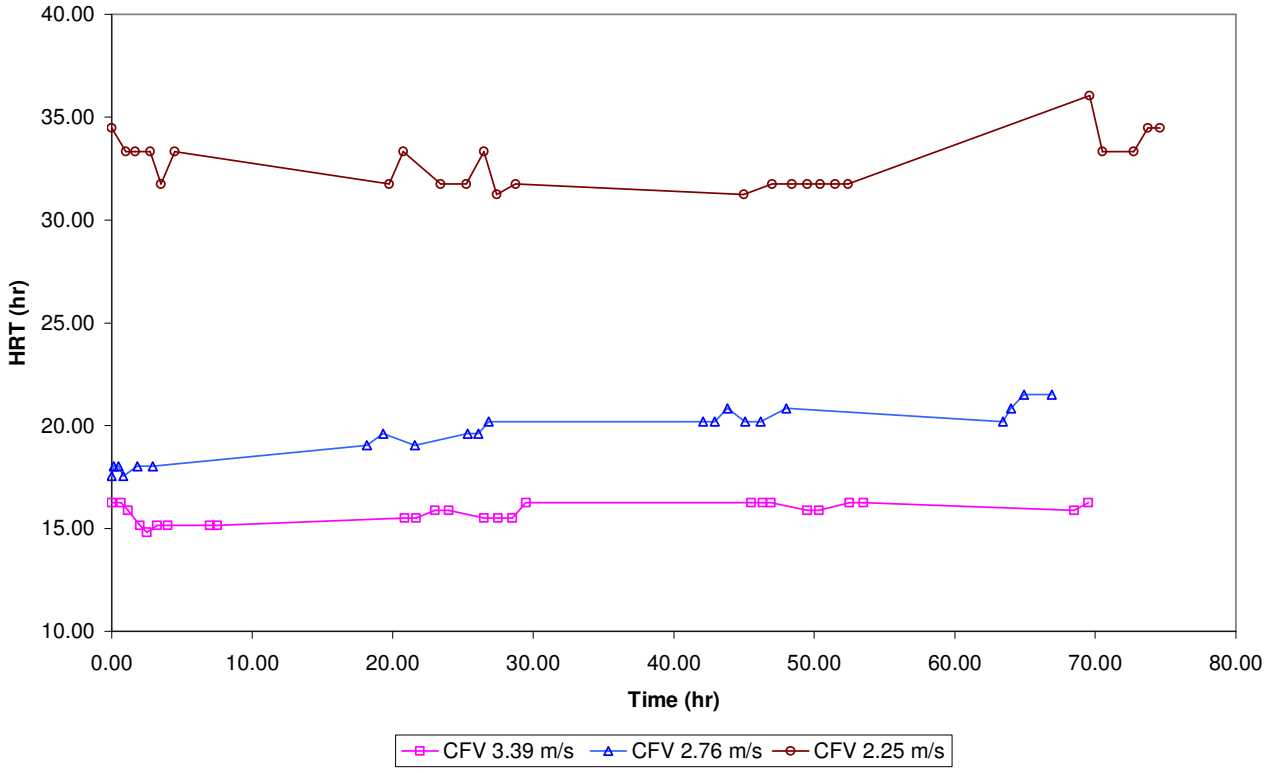

Figure 5.28: Variation of Hydraulic Retention Time (HRT) with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

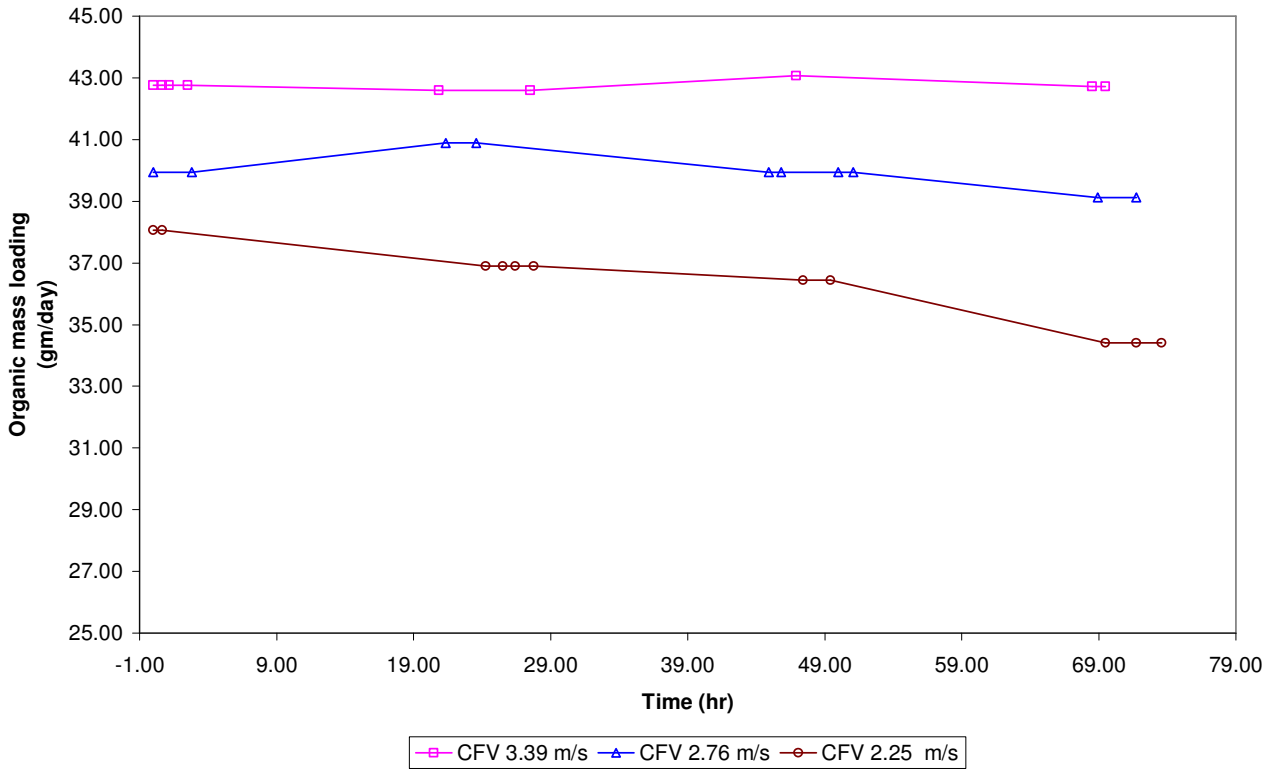

Figure 5.29: Variation of Influent Organic mass loading with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

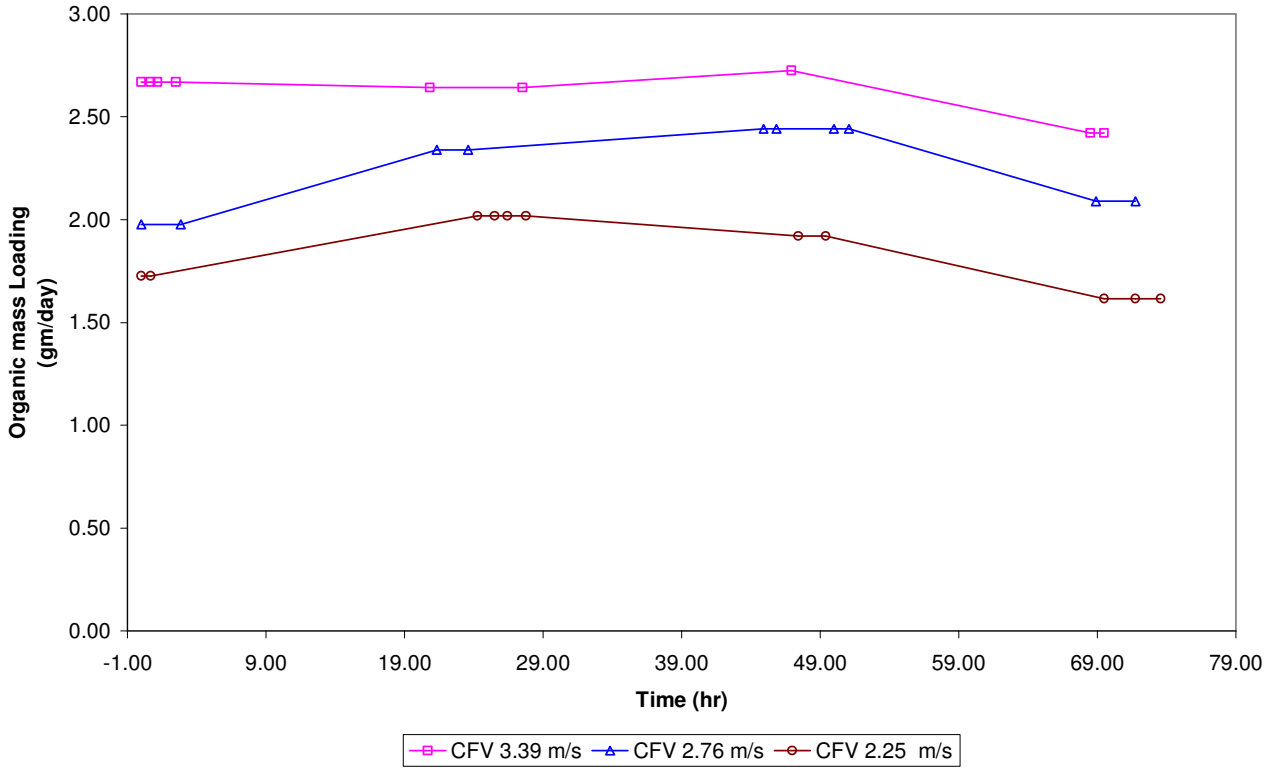

Figure 5.30: Variation of effluent Organic Mass Loading with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

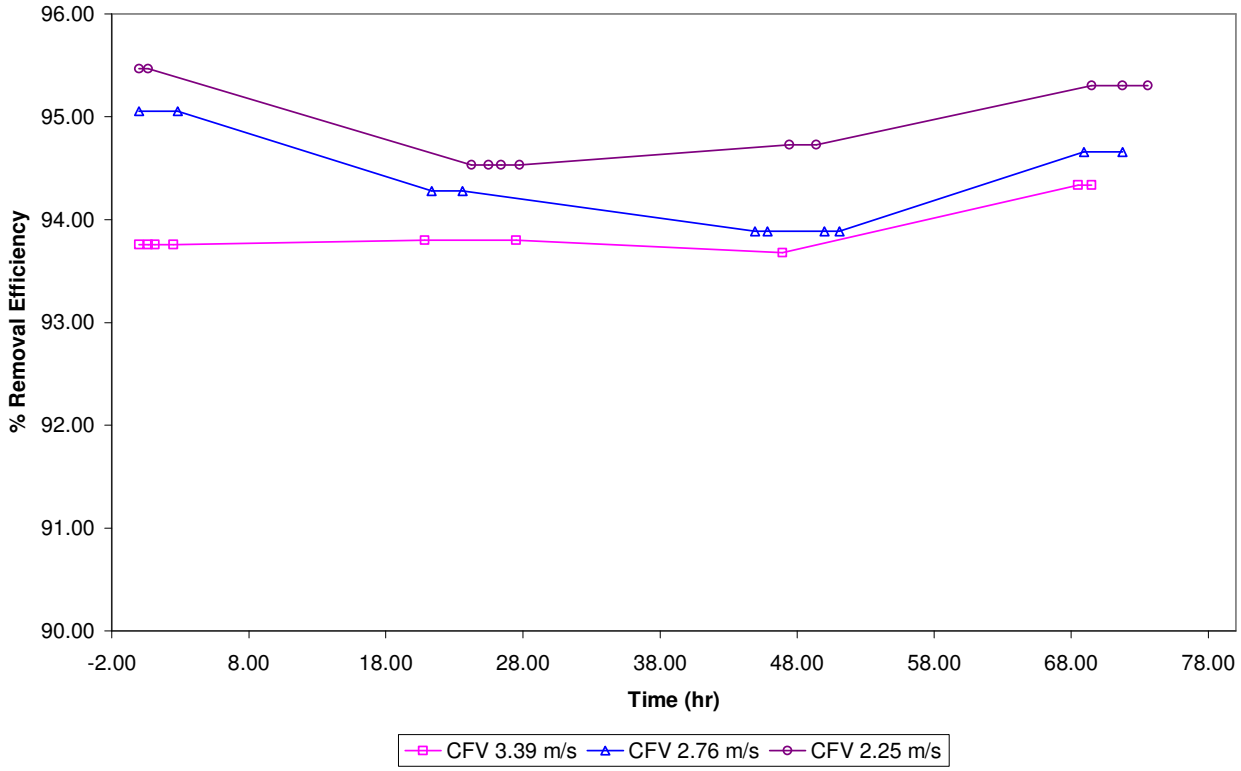

Figure 5.31: Variation of COD Removal Efficiency with time for different Crossflow Velocity (CFV) at MLSS of 3000 mg/L

Figures 5.32 to 5.34 represent variation of different operating conditions namely MLSS, SRT and pH during the study period. The MLSS concentrations shown in Figure 5.32 are the values obtained before the wasting of biomass. The average SRT values observed at MLSS of 5000 mg/l were 20, 23 and 67 day at CFV of 3.24, 2.69 and 2.21 m/s, respectively, while at MLSS of 3000 mg/l, the SRT values were 7, 24, and 31 days at CFV 3.39, 2.76 and 2.25 m/s, respectively. The measured pH was always in the range of 6-8.

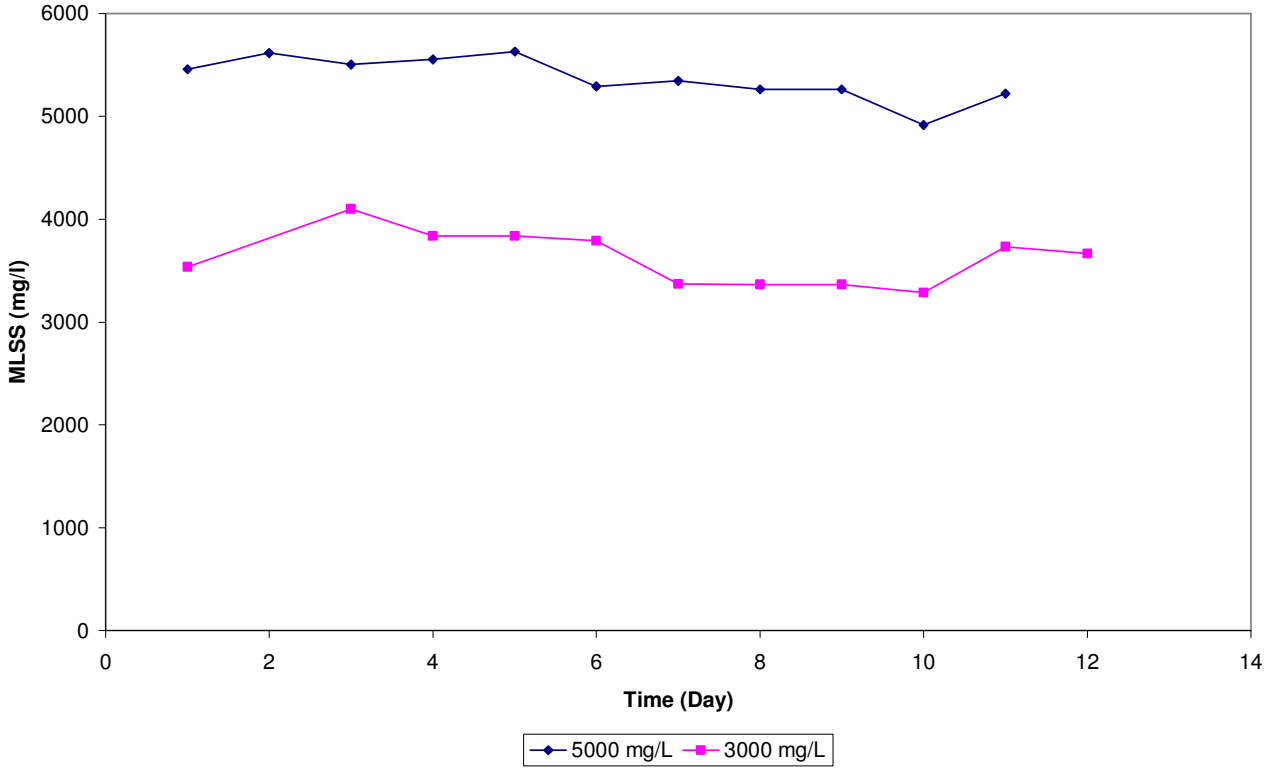

Figure 5.32: Variation of MLSS concentration (Before Wasting) with time

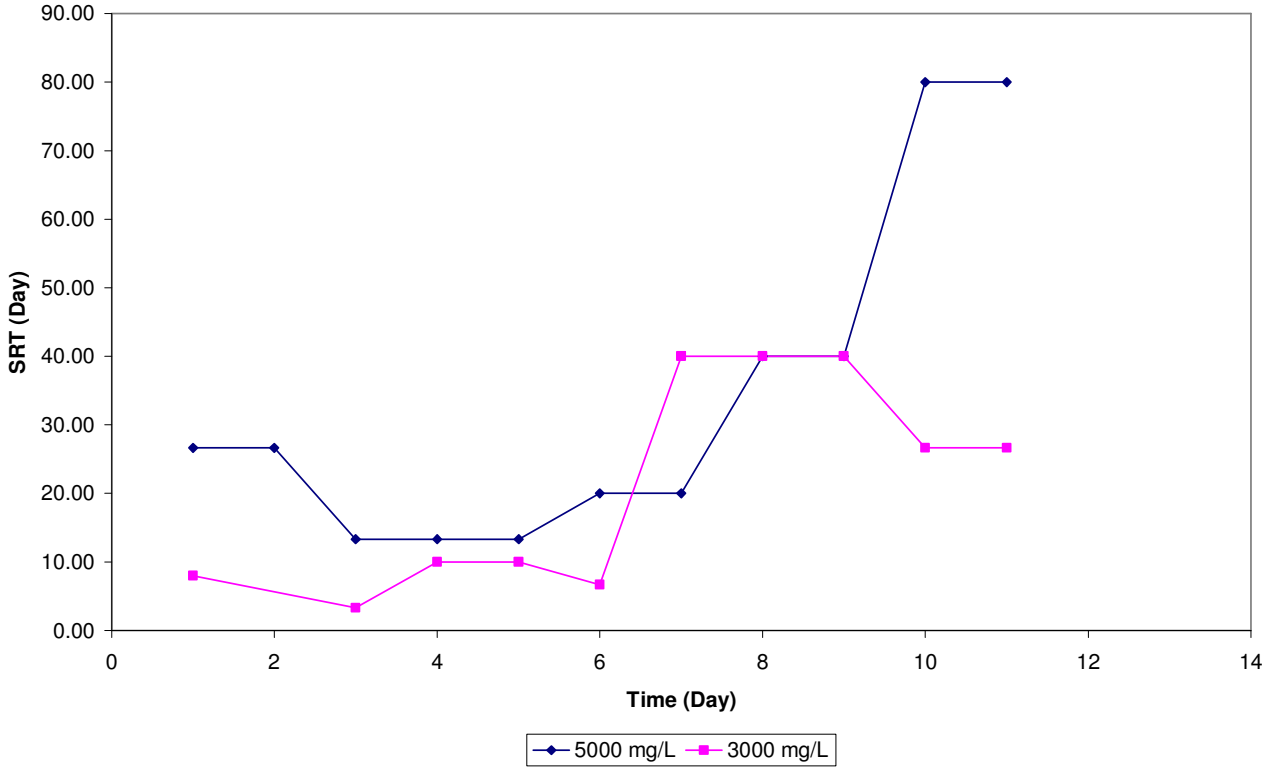

Figure 5.33: Variation of SRT with time

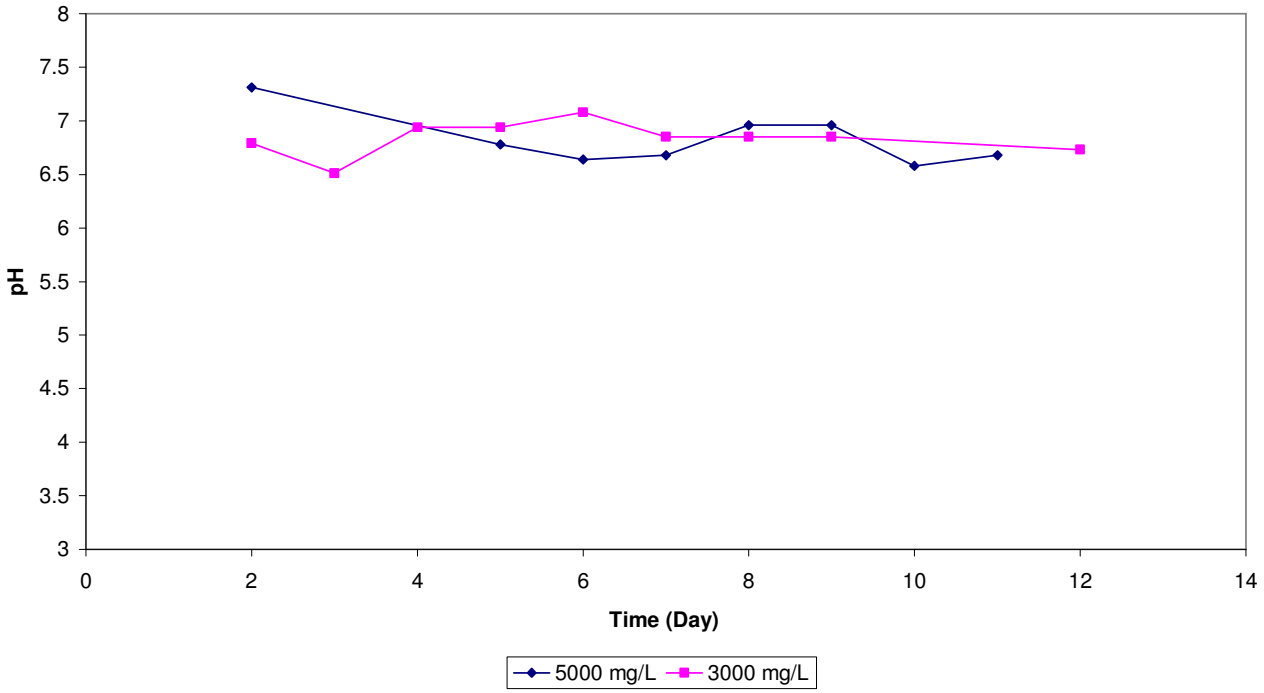

Figure 5.34: Variation of pH with Time

The dependency of flux on CFV could be described by the following power relation similar to that suggested in the literature review (section 2.5.1.4).

$$J \propto V^n$$

$$J = kV^n \qquad (5.23)$$

Where, J = Flux ($L/m^2/hr$)

V = crossflow velocity (m/s)

k, n = Constants

The steady state flux values at MLSS concentration of 5000 and 3000 mg/l were obtained from Figure 5.20 and 5.26 respectively, and summarized in Table 5.5. The data of Table 5.5 is plotted in Figure 5.35 and by linear regression k and n are determined and tabulated in Table 5.6. It is obvious from Table 5.6 that there is a definite relationship of MLSS concentration with the constants k and n. It can be seen that as the MLSS concentration increased, the values of the constants k and n decreased. In this study no mathematical relationship was developed between the MLSS concentration and the constants k and n, as only two MLSS concentrations were used. It is worth to mention that the value of constant k and n may only be used with this type of membrane and under similar conditions of investigation.

Table 5.5: Influence of Crossflow Velocity on Flux rate*

MLSS 5000 mg/l				**MLSS 3000 mg/l**			
Velocity, V (m/s)	Flux, J ($L/m^2/hr$)	Log (V)	Log (J)	Velocity, V (m/s)	Flux, J ($L/m^2/hr$)	Log (V)	Log (J)
3.24	72.00	0.51	1.86	3.39	84.00	0.53	1.92
2.69	55.00	0.43	1.74	2.76	65.00	0.44	1.81
2.21	39.00	0.34	1.59	2.25	41.00	0.35	1.61

* Data obtained from Figure 5.20 and 5.26 of steady state fluxes

Table 5.6: Results of k and n for different MLSS concentrations

MLSS (mg/l)	**k**	**n**	**R^2**
3000	11.30	1.75	0.973
5000	11.03	1.6	0.997

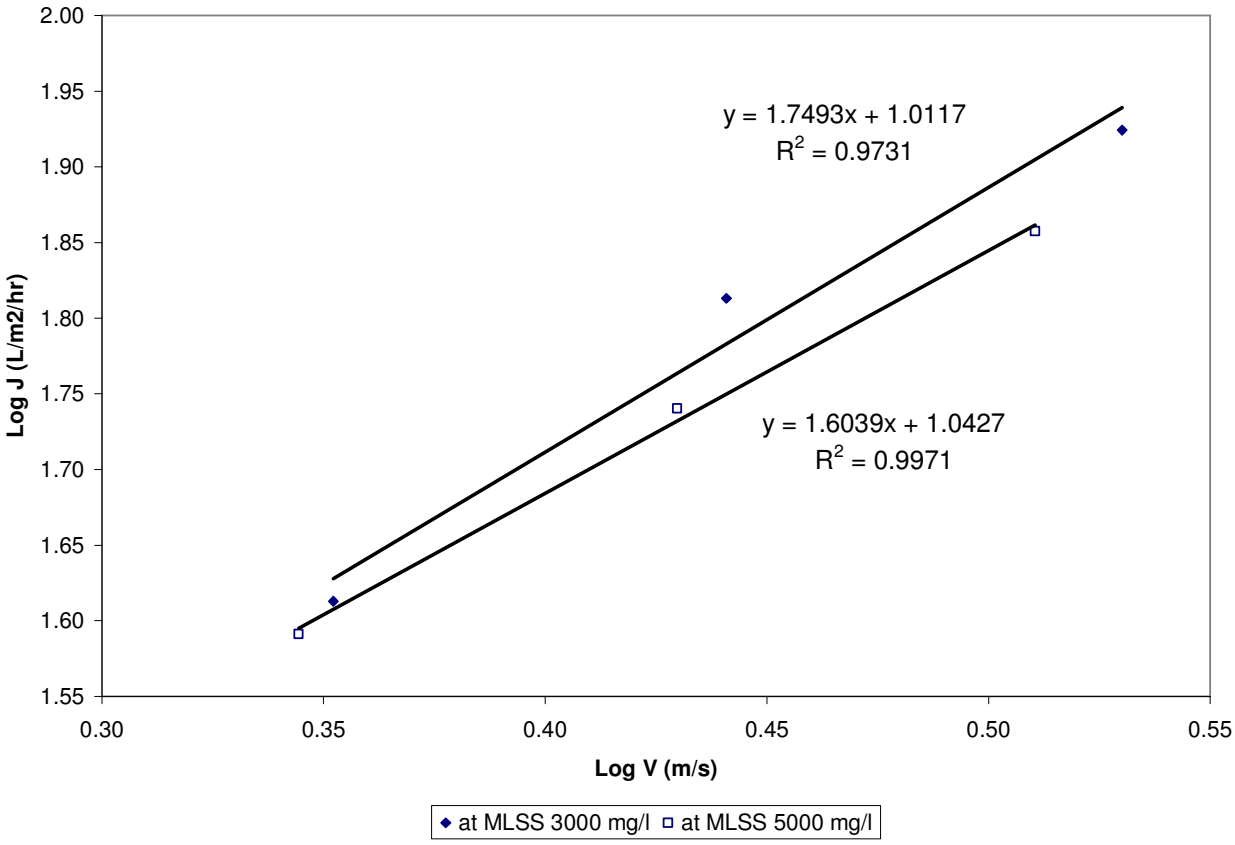

Figure 5.35: Influence of CFV on Flux rate

5.4 PERMEATE QUALITY PARAMETERS

5.4.1 Organic Constituent Analysis Of Permeate

During the kinetic coefficient study period, different parameters indicating the quality of permeate were examined. The major parameters tested were BOD, TOC, phenol, oil and grease and ammonia. Besides these, COD was also measured, which was a key element in the determination of biokinetic coefficient of the system and discussed in the preceding sections.

Figure 5.36 represents the variation of BOD in a typical day. The feed tank contained the glucose peptone based solution and the aeration tank contained the mixture of oil and feed thus representing the industrial waste rather than the domestic waste. That's why it is very customary that the feed tank BOD is more than that of aeration tank. It can be seen that the system has almost eliminated the BOD in permeate. On an average, the BOD in permeate was 0.8 mg/l.

Throughout the study period, the TOC in permeate varied between 10.4 and 31.3 mg/l, with a mean value of 19.2 mg/l. Phenol, oil & grease and ammonia were having mean values of 1.95, 2.04 and 7.88 respectively (Table 5.7).

5.4.2 Microbial Analysis of Permeate

For finding the viable bacterial count in the reactor as well as permeate, heterotrophic plate count method was adopted. The pour plates were incubated for 48 hours at 35^0C. Following the incubation, two types of survived colonies were found i.e. big spongy white colonies and small whitish yellow colonies.

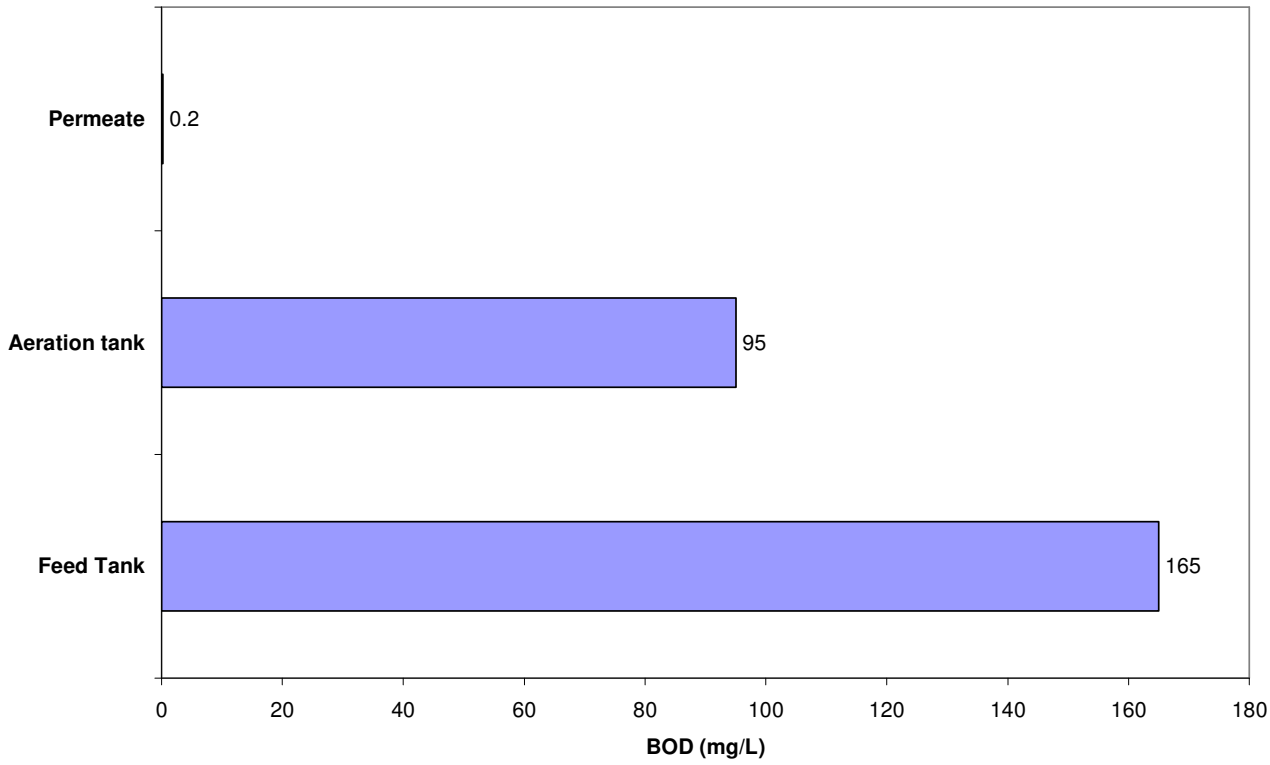

Figure 5.36: Variation of BOD in a typical day

Table 5.7: Permeate quality parameters

Parameter	Range (mg/l)	Mean Value (mg/l)
BOD	0.2-1.2	0.8
TOC	10.4-31.3	19.2
Phenol	0.85-3.75	1.95
Oil & grease	1.1-3.5	2.04
Ammonia	0.21-21.23	7.88

Figure 5.37 shows the variation of plate count result in both the aeration tank and permeate. It is noticeable from the figure that permeate plate count values are far less than the tank values. On an average one log reduction in permeate colony forming units were observed during the experimental period.

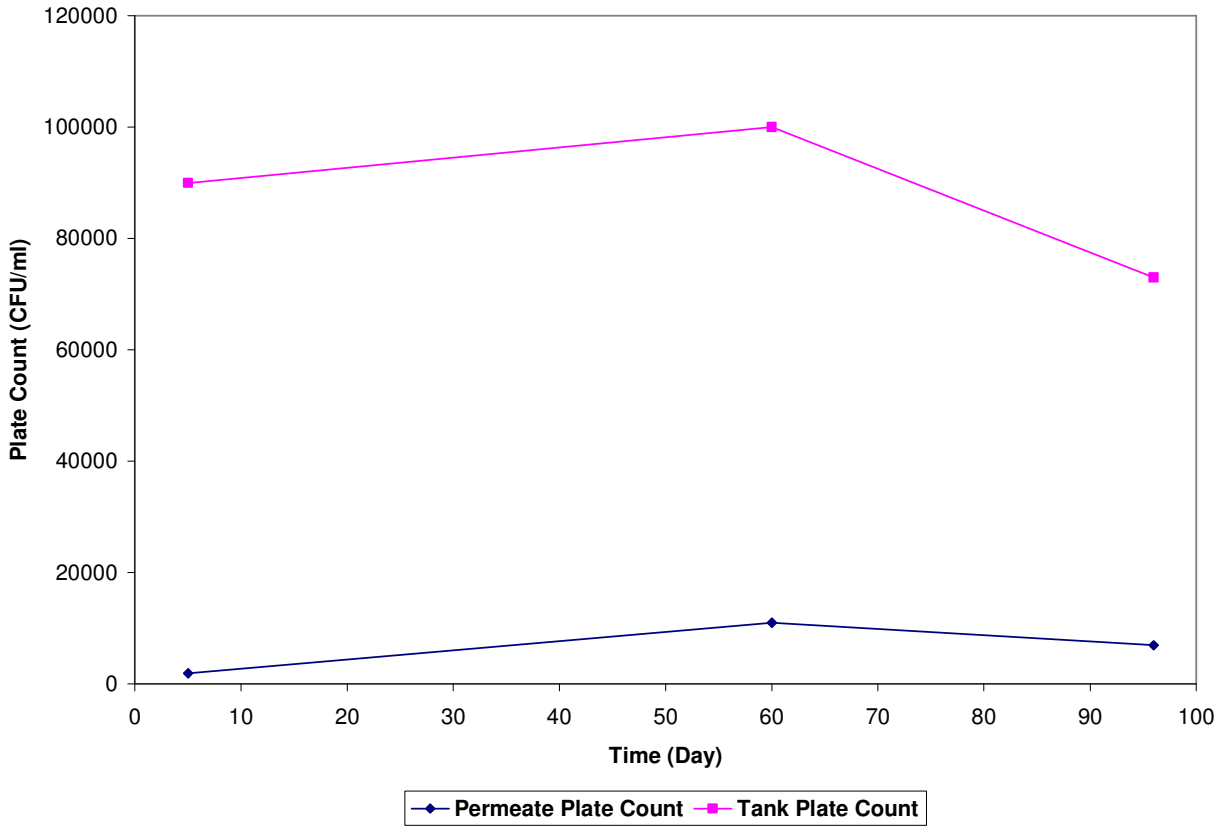

Figure 5.37: Standard Plate count in Permeate and Aeration Tank

5.5 MEMBRANE FOULING CONTROL

Permeate in microfiltration and ultrafiltration processes decreases with time as the retained particles accumulate in the membrane surface (Lee et. al., 2002). Because of this phenomenon, the MBR process needed to be stopped regularly for membrane cleaning to restore membrane permeability. The membrane unit was disconnected for cleaning when the flux dropped below a pre-specified value of 35 $L/m^2/hr$. Fouling of the membrane depends on the characteristics of foulant and membrane materials. In the study of MBR, the major contribution to fouling occurs from different solute fractions resulting from activated sludge. Three solute constituents can be distinguished among them i.e. suspended solid consisting mainly of bacterial flocs with a concentration depending upon the sludge age, colloids (polymers, fragments of lysed cells) and dissolved molecules. (Defrance et.al., 2000). Also many inorganic elements dissolved in oily waste can play a significant role in fouling the membranes. No investigation in this study was done for finding the foulant characteristics. But based on the literature, it was assumed that the fouling characteristics might be organic, inorganic or in combination of both and the cleaning agents were chosen keeping this fact in mind. As a rule, mineral deposits are removed by acidic solutions and organic compounds by alkaline solutions. (Lindau, J. and Jonsson, A.S, 1994).

At the beginning of this study the cleaning procedure was attempted by the use of CLOROX only. The CLOROX is sodium hypochlorite and effective for the removal of organic fouling. The procedure is represented in Figure 5.38 and in Table E1 (Appendix E) from which the variation of permeate flux can be observed during the cleaning.

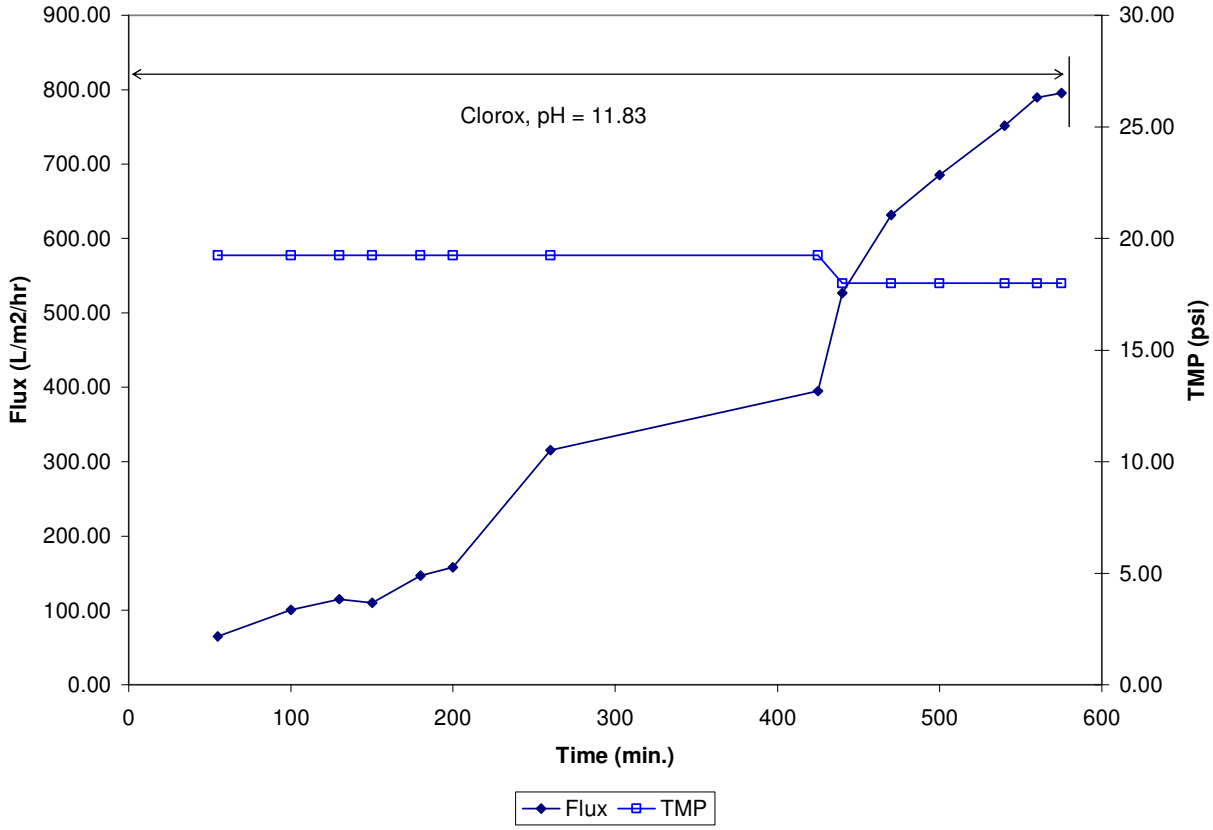

Figure 5.38: Variation of Flux during Cleaning with CLOROX

The cleaning process continued around 9.6 hrs to restore the flux as the new membrane. The flux of the new membrane with clean water was 947 L/m^2/hr at TMP 21.0 psi. As stated earlier, the pump used in this study was centrifugal pump in which the flow is varied in proportional to pressure. It is clear from Figure 5.38 that the TMP was almost constant with a slight drop of 1.25 psi throughout the cleaning procedure thus the same crossflow velocity prevailed. Therefore the increase in permeate flux was supposed to be the combination of the solubilization effect of the cleaning agent and the shear stress applied to the foulant layer (Lindau, J. and Jonsson, A.S, 1994) and it is not possible to distinguish between these two effects.

Although cleaning the membrane with CLOROX restored the flux significantly, yet the cleaning time was not satisfactory. To obtain a reasonable cleaning time it was decided to use different chemicals in succession. For this purpose a combination of PERSIL and CLOROX was tested in different sequence (run 1, run 2 and run 3) followed by clean water rinsing which are represented in the Figures 5.39, 5.40, 5.41 and Table E2 (Appendix E). In all of these cleaning procedures the temperature varied from 38 to 40^0 C which occurred within 90 minutes of the start of the process. The increase of the temperature was due to the recirculation of water for long time. It is evident from Figures 5.39 to 5.41 that cleaning time was improved during run 2 in comparing to run 1 and 3. Though the final flux of run 2 is less than that of run 1 yet it may happen because TMP of run 2 was 2.5 psi less than that of run 1. During the cleaning period, CLOROX was used for 227, 110 and 110 minutes in run 1, 2, 3, respectively, and PERSIL was used at 60, 75 and 65 minutes. Therefore cleaning the membrane with PERSIL for longer time might contribute in reducing the total cleaning time in run 2.

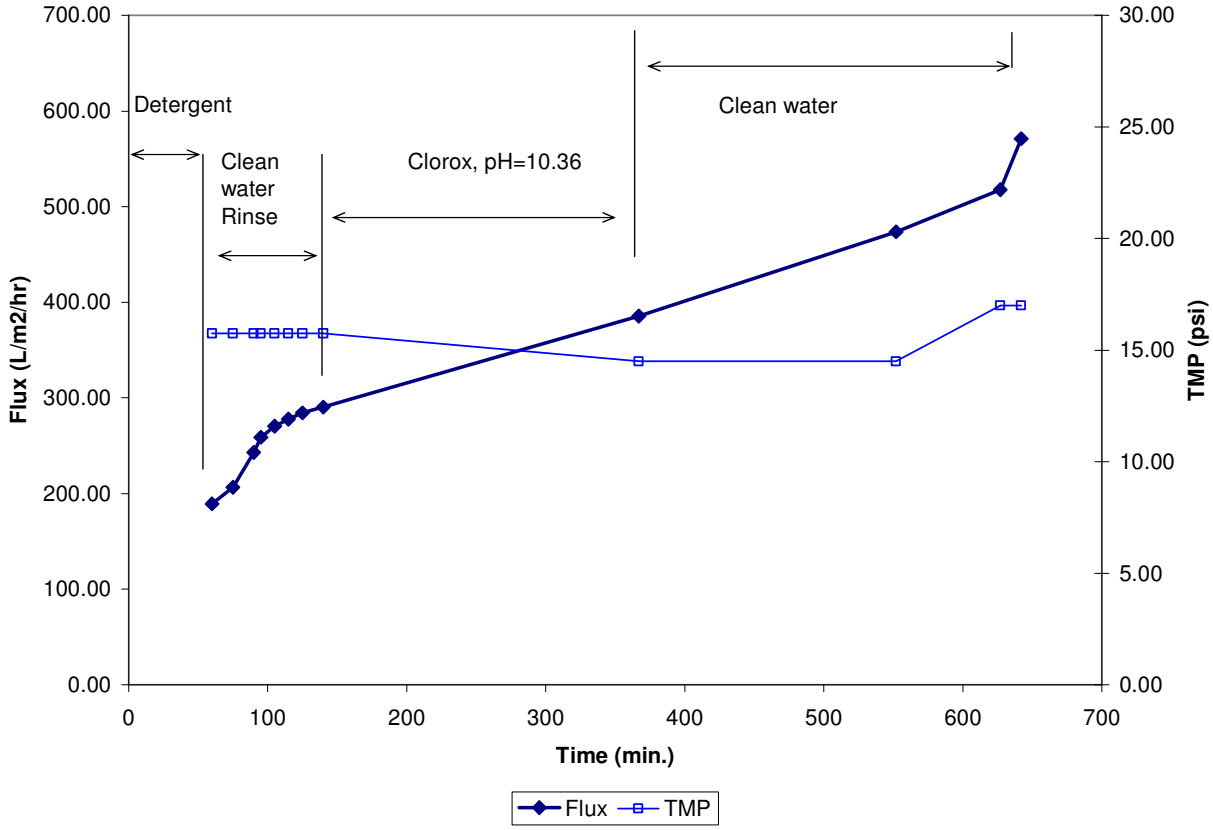

Figure 5.39: Variation of Flux during Cleaning with PERSIL and CLOROX, Run 1

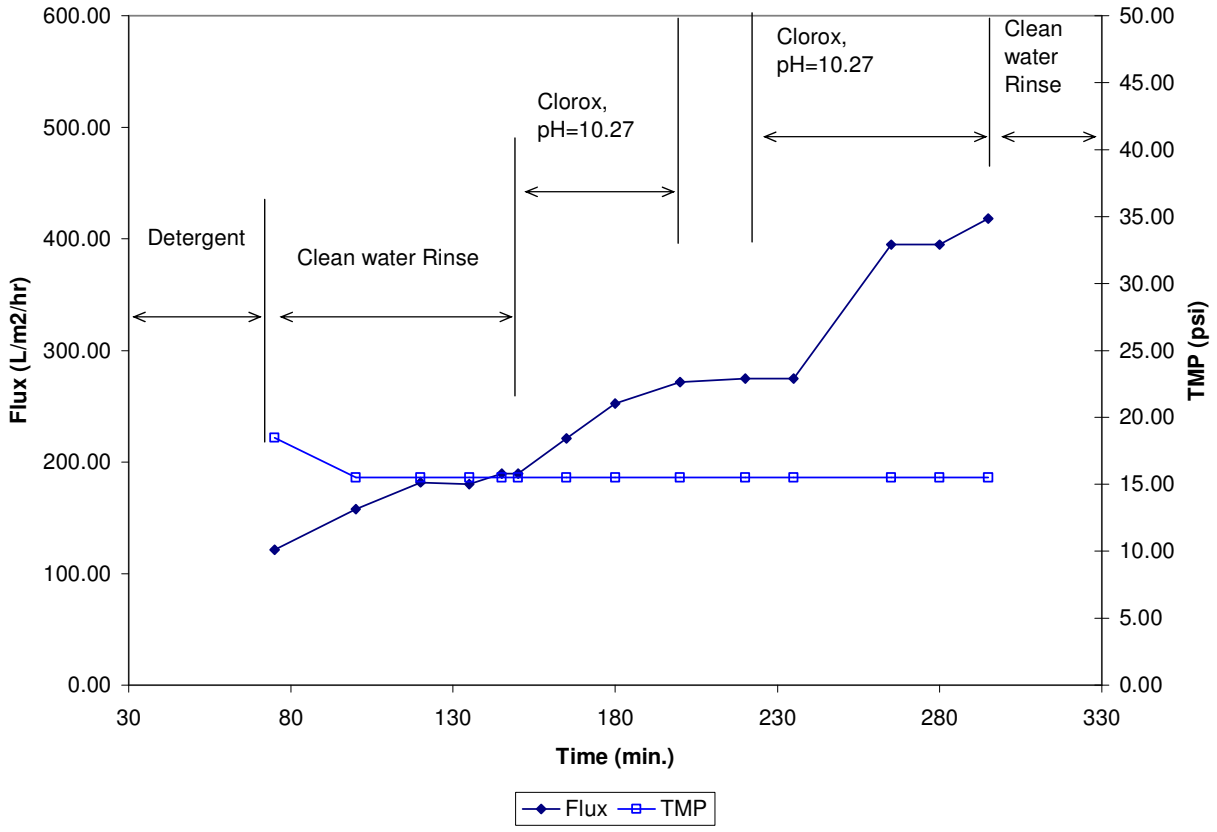

Figure 5.40: Variation of Flux during Cleaning with PERSIL and CLOROX, Run 2

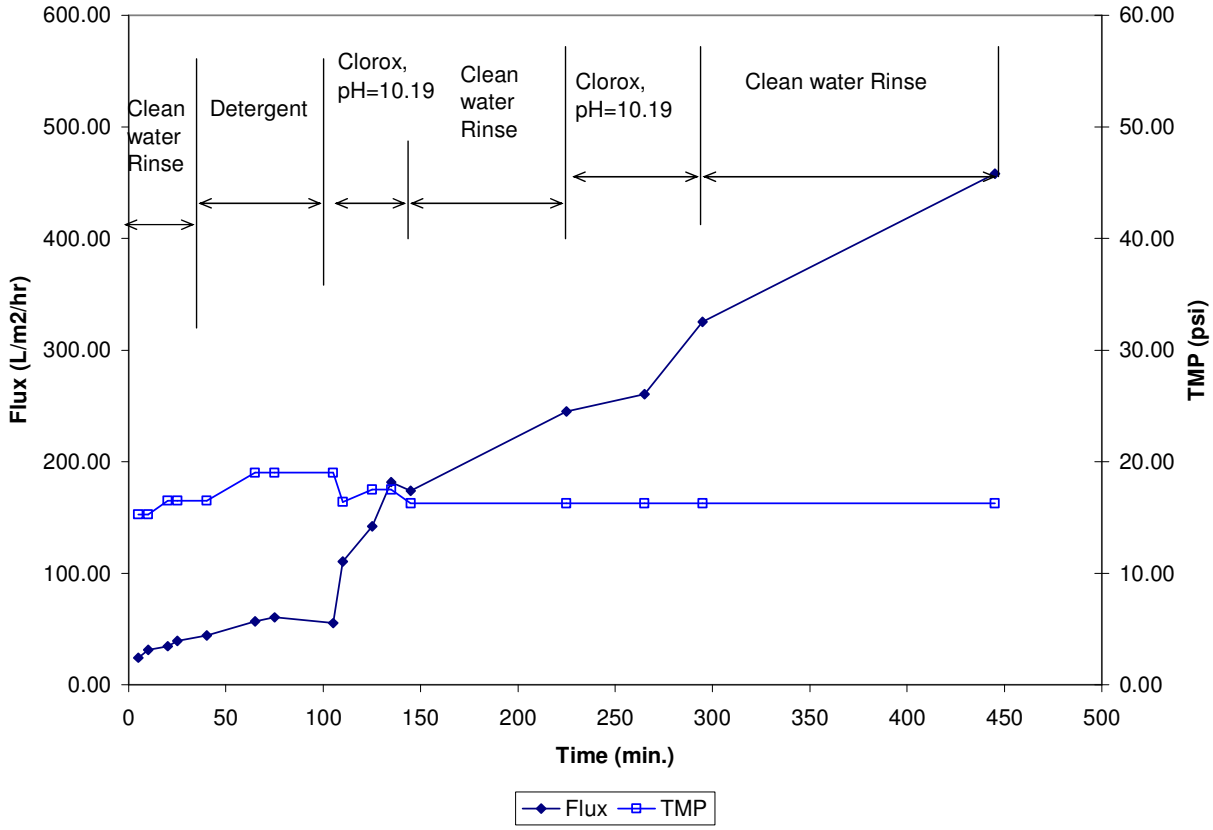

Figure 5.41: Variation of Flux during Cleaning with PERSIL and CLOROX Run 3

Figure 5.42 represents the summary of the cleaning procedure of run 1, 2 and 3. The data presented in this figure was used to estimate the flux recovery ($J_{cleaned}$ / $J_{uncleaned}$) based on the permeate flux of cleaned and uncleaned membrane (Lindau, J. and Jonsson, A.S, 1994). The figure also represents the clean water flux during the washing time which is much higher than permeate flux when connecting the membrane unit to the bioreactor. However the flux recovery was calculated on the basis of permeate flux of MBR rather than the clean water flux. The flux recovery calculated for run 1, 2 and 3 were 6.84, 4.46 and 7.08, respectively. It can be concluded that from the point of view of flux recovery, run 3 can be regarded as the most effective cleaning combination but when comes the question of washing time, run 2 is a better option. Also to be noted that after the application of cleaning combination of run 2, the system ran for 50 days without any cleaning (Figure 5.1) which was 13 and 5 days for run 1 and 3, respectively.

Another cleaning agent "SUPERCLEAN" was tested to improve the cleaning time and the flux restoration. This chemical cleaning was followed by backwashing of membrane as stated in Section 4.4.3. It can be observed in Figure 5.43 that washing the membrane with SUPERCLEAN caused the peak flux to be constant for around 27 hours thus established a wider peak than the previous cleaning agent (i.e. PERSIL and CLOROX). In relation to cleaning time, the SUPERCLEAN needed 84.7% less time than needed by the cleaning agent PERSIL and CLOROX to reinstate the flux (Figure 5.44) and also the flux recovery was almost the same. Therefore, combination of chemical washing with SUPERCLEAN followed by the backwash was regarded as the best solution for fouling control and adopted as the effective cleaning technique throughout the rest of the study period.

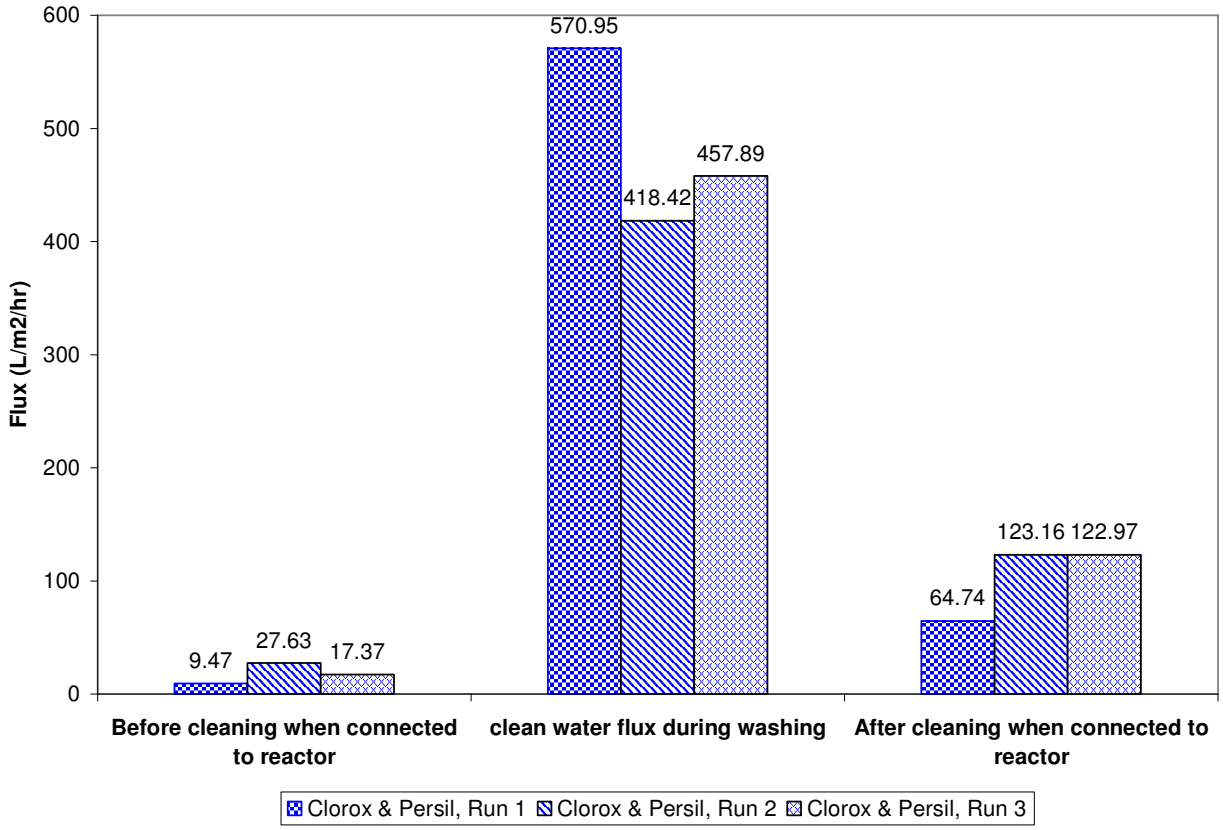

Figure 5.42: Summary of the cleaning procedure with the combination of PERSIL and CLOROX

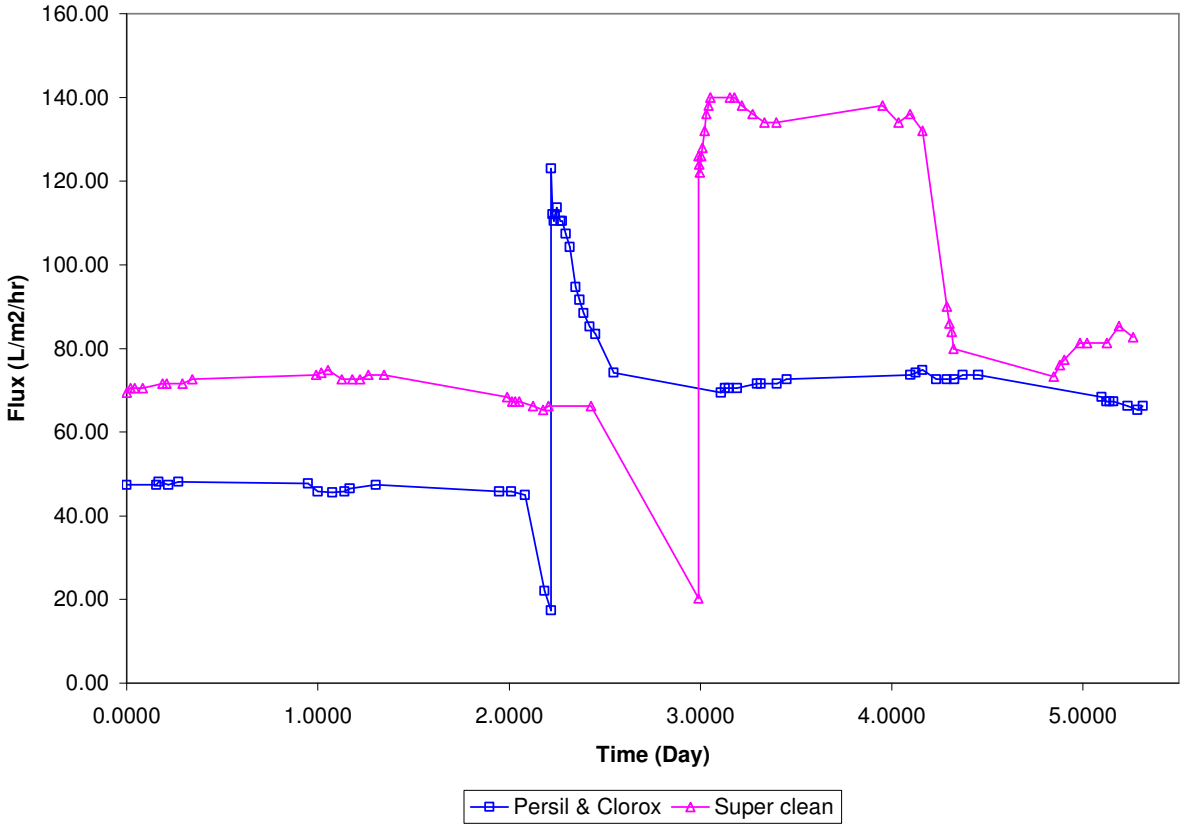

Figure 5.43: Variation of Flux Before and after Cleaning

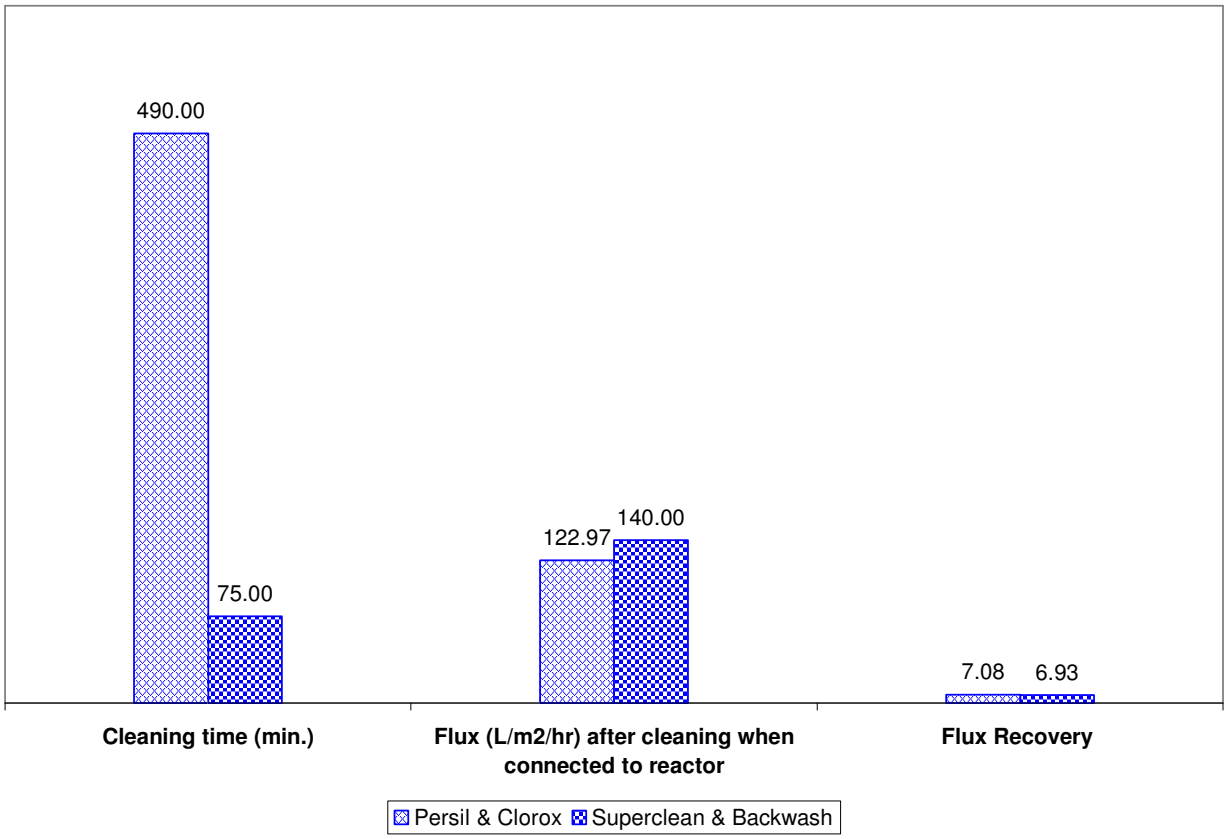

Figure 5.44: Summary of the cleaning procedure with PERSIL-CLOROX and SUPERCLEAN- and backwash

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The following conclusions can be made from the present study:

- During the biokinetic study period, high removal efficiency (93 – 94%) was observed. The removal efficiency was not improved with increasing the MLSS concentration.
- Based on the Monod's Equation, kinetic coefficients Y, k_d, μ_m and K_S were determined. It was noted that the kinetic coefficients changed with the change in MLSS concentrations.
- The simulation study showed good agreement between model predictions and experimental data. The model can be used to simulate and investigate different operational strategies.
- Flux increased with the increase in cross-flow velocity and thus can be expressed by the power law relationship ($J = kV^n$). The constants k and n were found to be dependent on MLSS concentrations.
- COD Removal efficiency was found to be independent of HRT at different MLSS concentration in this study.

- The standard plate count showed one log reduction in permeate colony forming units during the experimental period which is not satisfactory.
- Chemical washing with "SUPERCLEAN" followed by the backwash was regarded as the best solution for fouling control in sense of cleaning time and recovered flux and adopted as the effective cleaning technique throughout the study period.

6.2 RECOMMENDATIONS

This research points towards the need for further investigations in the following areas:

- The ability of the system to withstand shock loading needs to be investigated.
- In the current investigation, the influent oil was supplied intermittently, which can be avoided by diluting the oil to some solvent (i.e. surfactant). Surfactant dilutes the oil fully hence the influent concentration can be controlled easily. In that situation the acclimatization of microorganism to the surfactant is a key issue.
- The COD removal efficiency was found almost same in the current study at MLSS 3000 and 5000 mg/l; higher concentration of MLSS (10,000 to 15,000 mg/l) may be used to further study the effect of MLSS concentration on COD removal.
- In the current study continuous measure of backwash in fouling removal of membrane could not be applied, because of unavailability of membrane housing. Further investigation for the application of backwashing in fouling control may be carried out.
- Investigation is needed for the economy of CF-MBR system.

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APPENDIX A

Standard Operating Procedure (SOP) of Modified Approach of Closed Reflux Titrimetric Method for COD Determination of Oily Waste from Petroleum Refinery

1.0 SCOPE AND APPLICATION

This modified closed reflux titrimetric method covers the COD determination of oily waste, which is volatile in nature and contain high COD (COD>10^6 mg/l). The method is helpful for the COD determination of refinery oily waste.

2.0 SUMMARY

In this method the sample is refluxed in concentrated sulfuric acid (H_2SO_4) with an excess of 1 N potassium dichromate ($K_2Cr_2O_7$). After digestion, the remaining unreduced $K_2Cr_2O_7$ is titrated with 0.25 N ferrous ammonium sulfate (FAS) to determine the amount of $K_2Cr_2O_7$ consumed and the oxidizable organic matter is calculated in terms of oxygen equivalent.

3.0 INTERFERENCES

3.1 The difficulties caused by the presence of the halides can be overcome by complexing with mercuric sulfate ($HgSO_4$) before the refluxing procedure.

3.2 To eliminate a significant interference due to nitrite (NO^{-2}), sulfamic acid can be used.

4.0 EQUIPMENT AND SUPPLIES

4.1 Digestion vessels: 250 ml long glass digestion tubes

4.2 Heating block: cast aluminum, 45 to 50 mm deep, with holes sized for close fit of digestion tubes operates at 150 ± 2^0C in a block heater.

4.3 Parafilm “M”, laboratory film [American can Co.]

4.4 500 ml Erlenmeyer flask for titration

4.5 Stirrer with variable speed

4.6 TFE-covered magnetic stirring bar

4.7 20, 25, 50 and 100 ml graduated glass pipette

4.8 0.1 and 0.05 ml tip

4.9 25 ml Titration glass burette

4.10 100 ml graduated glass cylinder

4.11 500 ml volumetric flask

4.12 Glass funnel

4.13 Water bath

5.0 REAGENTS AND STANDARDS

5.1 *Standard potassium dichromate digestion solution,* 1.0 *N:* Dissolve 12.259 g $K_2Cr_2O_7$, primary standard grade and previously dried at 103^0C for 2 hrs, in deionized water and dilute to 250 ml.

5.2 *Silver sulfate (Ag_2SO_4):* Reagent or technical grade, crystal or powdered.

5.3 *Sulfuric acid reagent:* Add 5.5 g Ag_2SO_4 in powdered form in one kg conc. H_2SO_4 and stir for 15-30 minutes to dissolve.

5.4 *Ferroin indicator solution*

5.5 *Standard ferrous ammonium sulfate (FAS) titrant,* approximately 0.25 N: Dissolve 98 g $Fe(NH_4)_2(SO_4)_2.6H_2O$ in deionized water. Add 20 ml conc. H_2SO_4 to this solution, cool to room temperature and dilute to 1000 ml.

6.0 CALIBRATION AND STANDARDIZATION

6.1 Standardize the FAS solution daily against the standard $K_2Cr_2O_7$ solution. For this purpose, dilute 10.0 ml of $K_2Cr_2O_7$ to about 100 ml. Add 30 ml of conc. H_2SO_4 and cool to room temperature. Titrate with FAS using 2 to 3 drops of Ferroin indicator.

Normality of FAS solution

$$= \frac{\text{Volume of 1.0 N } K_2Cr_2O_7 \text{ solution titrated, ml}}{\text{Volume of FAS used in titration, ml}} \text{ x Normality of } K_2Cr_2O_7$$

7.0 PROCEDURE

7.1 Wash digestion tubes and dry.

7.2 Add 40 ml of 1 N $K_2Cr_2O_7$ using 20 ml graduated glass pipette in the digestion tubes.

7.3 Hold the digestion tube at 45^o angle and slowly add around 25 ml H_2SO_4, rotating the digestion tube to thorough mixing of acid with $K_2Cr_2O_7$. Place the tube in water bath. Repeat the procedure to complete the total addition of 75 ml H_2SO_4.

7.4 Check the tubes containing the H_2SO_4 and $K_2Cr_2O_7$ solution are cooled to room temperature before adding the sample.

7.5 Add 0.1 or 0.05 ml sample in the digestion tube with the help of pipette tips. Do not add any sample in the tubes considered as blank. Cap the tube immediately with two to three number of Parafilm. Place the palm on the mouth of the tube tightly and invert each several times to mix the sample with the solution completely.

7.6 Place the tubes in block digester preheated to 150^0C and reflux for 2 hours.

7.7 After the completion of digestion, cool the tubes to room temperature and place in the test tube rack.

7.8 Remove the Parafilm caps and collect the solution sticking to Parafilm after washing with deionized water.

7.9 For the purpose of titration, dilute the contents in the tubes to 500 ml in volumetric flask. Pipette 100 ml of the diluted solution in the Erlenmeyer flask for titrating the 0.1 ml sample (use 50 ml of diluted sample for titrating 0.05 ml sample and that of 25 ml for the blank).

7.10 Add TFE-covered magnetic stirring bar in the Erlenmeyer flask. Stir rapidly on magnetic stirrer while titrating with 0.25 N FAS after adding two to three drops of Ferroin indicator. The end point is a sharp color change from blue-green to reddish brown, although the blue green may reappear within minutes.

8.0 CALCULATIONS

$$\text{COD as mg } O_2/l = \frac{(A-B) \times M \times 8000}{\text{ml sample}}$$

Where,

A =ml FAS used for blank

B = ml FAS used for sample

M = Normality of FAS

9.0 POLLUTION PREVENTION AND WASTE DISPOSAL

9.1 Placing the sample in the digestion tubes and the digestion must be carried out under a fume hood.

9.2 The waste liquids must be collected in waste-collection receptacles and disposed through the university waste disposal program.

10.0 DATA VALIDATION AND REPORTING

Data generated in the analysis will be reviewed and signed by the supervisor.

11.0 HEALTH AND SAFETY

11.1 Concentrated H_2SO_4 presents various hazards and is moderately toxic and is extremely to skin and mucus membranes. This reagent should be used in a fume hood and handled with gloves and safety glasses.

11.2 Attention is to be paid to protect the hands from heat produced when adding and mixing the conc. H_2SO_4 to $K_2Cr_2O_7$.

11.3 Mix the content of the digestion tube thoroughly before applying heat to prevent local heating of the tube bottom and possible explosive reaction.

12.0 REFERENCES

APHA; Standard Methods, for the examination of water and wastewater; Nineteenth edition, American Public Health association, Washington D.C., 1995.

APPENDIX B

RAW DATA FOR BIOKINETIC STUDIES

Table B1: Raw data for Biokinetic studies at MLSS 5000 mg/L

Time (Day)	Average Influent loading gm/day	Effluent COD (mg/L)	Average Effluent loading gm/day	Average Volume of food (L)	MLSS before wasting (mg/L)	MLSS after wasting (mg/L)	SRT (Day)
1	24	204	4.04	19.82	5324	5040	20.00
2	24	149	2.95	19.82	5420	4993	13.33
3	24	118	2.34	19.82	4930	4930	100.00
4	24	118	2.34	19.82	5107	4200	100.00
5	24	101	2.00	19.82	5066	5066	150.38
6	24	95	1.88	19.82	4953	4953	150.38
7	24	99	1.95	19.82	4453	4453	150.38
8	24	127	2.51	19.82	4793	4793	150.38
9	24	120	2.37	19.82	4540	4540	150.38
10	24	116	2.30	19.82	4433	4080	150.00
11	24	95	1.88	19.82	5106	4580	40.00
12	24	92	1.82	19.82	4660	4587	100.00
13	24	94	1.87	19.82	4983	4983	160.00
14	24	93	1.84	19.82	4960	4830	160.00
15	39	96	3.31	34.40	4880	5467	100.00
16	39	113	3.90	34.40	5133	5487	40.00
17	39	99	3.41	34.40	5267	5393	25.00
18	39	78	2.68	34.40	5273	5360	16.67
19	39	68	2.34	34.40	5787	5467	11.11
20	39	68	2.34	34.40	5030	5120	100.00
21	39	73	2.51	34.40	5526	5740	11.11
22	39	75	2.58	34.40	5673	5420	11.11
23	44	86	2.82	32.75	5095	5687	50.00
24	44	84	2.75	32.75	5494	5400	13.33
25	44	81	2.66	32.75	5500	5300	13.33
26	44	86	2.82	32.75	5113	4943	25.00
27	44	124	4.06	32.75	3373	3373	80.00
28	59	112	3.53	31.50	3407	3704	40.00
29	59	117	3.69	31.50	3400	3400	40.00
30	57	222	7.01	31.50	5493	4920	40.00
31	57	125	3.93	31.50	4767	4473	100.00
32	57	112	3.53	31.50	4727	4727	80.00
33	57	99	3.12	31.50	4967	4747	80.00
34	57	220	6.92	31.50	4033	4033	80.00
35	57	112	3.53	31.50	4167	4167	80.00
36	57	112	3.53	31.50	4640	4640	80.00
37	57	140	4.41	31.50	5207	4893	80.00
38	57	118	3.72	31.50	5460	5287	13.33

Table B1: Raw data for Biokinetic studies at MLSS 5000 mg/L

Time (Day)	Average Influent loading gm/day	Effluent COD (mg/L)	Average Effluent loading gm/day	Average Volume of food (L)	MLSS before wasting (mg/L)	MLSS after wasting (mg/L)	SRT (Day)
39	57	115	3.63	31.50	5427	4800	13.33
40	57	111	3.49	31.50	5327	4923	18.18
41	57	109	3.45	31.50	5417	4866	14.29
42	57	110	3.46	31.50	5460	4900	13.33
43	57	108	3.39	31.50	5367	4976	15.38
44	67	108	2.65	24.59	5667	4826	9.09
45	67	173	4.25	24.59	5430	5096	13.33
46	67	234	5.76	24.59	5550	4873	10.00
47	67	122	3.00	24.59	5233	5068	25.00
48	67	117	2.89	24.59	5533	5012	11.11
49	67	123	3.02	24.59	5640	5067	9.09
50	67	118	2.90	24.59	5580	4885	9.09
51	67	120	2.94	24.59	5347	4986	13.33
52	67	120	2.95	24.59	5680	5074	9.09
53	67	124	3.05	24.59	5438	4921	12.50

Table B2: Raw data for Biokinetic studies at MLSS 3000 mg/L

Time (Day)	Average Influent loading gm/day	Effluent COD (mg/L)	Average Effluent loading gm/day	Average Volume of food (L)	MLSS before wasting (mg/L)	MLSS after wasting (mg/L)	SRT (Day)
1	30	82	2.62	31.98	3300	3207	40.00
2	30	83	2.64	31.980	3647	3973	28.57
3	30	84	2.70	31.980	3723	3793	25.00
4	30	86	2.76	31.980	3494	3693	50.00
5	30	78	2.48	31.980	3556	3667	50.00
6	36	69	1.89	27.39	3587	3526	25.00
7	36	68	1.86	27.390	3433	3393	50.00
8	36	72	1.97	27.390	3546	3620	50.00
9	36	70	1.92	27.390	3620	3360	20.00
10	39	91	2.03	22.43	3060	3480	25.00
11	39	106	2.39	22.430	3353	3156	16.67
12	39	102	2.30	22.430	3066	2804	40.00
13	39	93	2.09	22.430	3187	2980	25.00
14	39	93	2.09	22.430	3007	3193	40.00
15	39	89	2.00	22.430	3293	2967	20.00
16	39	98	2.19	22.430	3120	2900	25.00
17	39	96	2.15	22.430	2920	2773	25.00
18	39	92	2.06	22.430	2880	2654	33.33
19	47	114	2.46	21.65	2687	2973	50.00
20	47	110	2.38	21.650	2616	2716	50.00
21	47	104	2.25	21.650	2947	3153	33.33
22	47	95	2.06	21.650	2960	2733	25.00
23	47	102	2.21	21.650	3067	3247	16.67
24	47	104	2.25	21.650	3033	3347	16.67
25	47	101	2.19	21.650	2953	3180	20.00
26	53	99	2.35	23.69	2733	3187	20.00
27	53	99	2.35	23.690	3227	2380	20.00
28	53	106	2.51	23.690	3233	2973	20.00
29	53	114	2.70	23.690	2700	2833	40.00
30	53	120	2.84	23.690	3180	2907	20.00
31	53	71	1.68	23.690	2827	2907	25.00
32	53	113	2.68	23.690	3293	2880	11.11
33	53	110	2.61	23.690	3147	2847	12.50
34	53	108	2.56	23.690	3233	2860	12.50
35	65	128	4.23	32.98	3933	3153	6.67
36	65	112	3.70	32.980	4313	3086	4.00
37	65	118	3.90	32.980	3910	3100	3.64
38	65	136	4.49	32.980	3680	2994	5.71

Table B2: Raw data for Biokinetic studies at MLSS 3000 mg/L

Time (Day)	Average Influent loading gm/day	Effluent COD (mg/L)	Average Effluent loading gm/day	Average Volume of food (L)	MLSS before wasting (mg/L)	MLSS after wasting (mg/L)	SRT (Day)
39	65	126	4.16	32.980	3840	3052	5.00
40	65	124	4.10	32.980	3759	2860	5.00
41	65	118	3.90	32.980	3348	3167	9.09
42	65	117	3.87	32.980	3463	2803	8.00
43	65	115	3.81	32.980	3476	3137	8.00
44	65	115	3.81	32.980	3240	2942	11.11

Table B3: Variation of Temperature, pH and Dissolved oxygen during the experimental period

Day	Temp.	Day	pH	Day	DO
1	40.25	4	6.47	10	6.42
2	41.00	11	7.16	16	7.20
3	38.00	16	7.24	33	4.15
4	38.50	25	6.60	44	6.62
5	38.50	26	6.41	53	7.24
6	39.00	28	7.28	68	4.20
7	39.00	29	6.46	79	4.11
8	39.00	30	6.52	81	4.01
9	39.00	32	6.48	83	4.25
10	39.00	33	6.41		
11	40.00	34	6.52		
12	40.00	35	6.52		
15	43.00	36	6.52		
16	43.50	37	6.56		
17	42.00	38	6.43		
18	39.00	39	6.36		
19	41.00	40	6.72		
20	41.00	41	6.35		
21	41.00	42	6.49		
23	42.00	43	6.42		
24	44.00	44	6.45		
25	41.00	46	6.31		
26	44.00	47	6.32		
27	40.00	48	6.49		
28	42.00	49	6.48		

Day	Temp.	Day	pH
29	41.00	50	6.50
31	41.00	51	6.74
33	40.00	52	6.74
34	42.00	53	7.10
36	42.00	54	7.20
37	42.00	55	7.20
38	42.00	56	7.15
39	46.00	57	7.13
41	44.00	59	7.20
42	45.00	60	7.14
43	44.00	61	7.14
44	44.00	65	7.48
46	44.00	66	7.35
49	44.00	67	7.15
51	44.00	72	6.74
52	44.00	73	7.18
53	43.50	79	6.81
54	43.00	80	6.91
55	43.00	83	7.60
60	44.00	86	7.70
64	43.00	87	7.51
66	44.00		
72	45.00		
73	45.00		
79	46.00		
81	47.00		

APPENDIX C

RAW DATA FOR HYDRAULIC PERFORMANCE OF CF-MBR SYSTEM

Cumulative Time (day)	Flux ($L/m^2/hr$)	HRT (hr)	Turbidity (NTU)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure,TMP (psi)
0.0000	64.74	16.26	0.84	26.00	9.00	17.50
0.0069	64.74	16.26	0.59	32.00	10.50	21.25
0.0139	62.37	16.88	0.94	34.00	11.50	22.75
0.0208	60.00	17.54	0.76	34.00	11.50	22.75
0.0278	60.95	17.27	0.81	34.00	11.50	22.75
0.0382	59.21	17.78	0.84	35.00	11.50	23.25
0.0486	60.13	17.51	0.65	35.00	11.50	23.25
0.0590	60.00	17.54	0.74	36.00	12.00	24.00
0.0729	59.43	17.71	0.96	36.00	12.00	24.00
0.0833	60.00	17.54	0.86	36.00	12.00	24.00
0.0938	60.00	17.54	0.97	36.00	12.00	24.00
0.1042	59.21	17.78	0.67	36.00	12.00	24.00
0.1250	57.63	18.26	0.77	36.00	12.00	24.00
0.1458	56.05	18.78	0.95	36.00	12.00	24.00
0.1667	54.47	19.32	0.87	36.00	12.00	24.00
0.1875	48.16	21.86	0.54	36.00	12.00	24.00
0.2083	45.79	22.99	0.51	36.00	12.00	24.00
0.2292	45.00	23.39	0.51	36.00	12.00	24.00
0.2500	45.00	23.39	0.73	36.00	12.00	24.00
0.2708	43.42	24.24	0.71	34.00	11.00	22.50
0.3125	45.00	23.39	0.80	34.00	11.00	22.50
0.3333	45.00	23.39	0.72	34.00	11.00	22.50
0.3542	45.79	22.99	0.84	34.00	10.50	22.25
0.3750	45.79	22.99	0.61	34.00	10.50	22.25
0.3958	45.00	23.39	0.68	34.00	10.50	22.25
0.4271	45.00	23.39	0.41	34.00	10.50	22.25
0.9201	43.42	24.24	0.46	32.00	10.00	21.00
0.9688	43.42	24.24	0.30	32.00	10.00	21.00
1.0104	43.42	24.24	0.38	32.00	10.00	21.00
1.0521	42.98	24.49	0.36	32.00	10.00	21.00
1.0938	44.21	23.81	0.35	32.00	10.00	21.00
1.1354	42.63	24.69	0.39	32.00	10.00	21.00
1.1771	42.95	24.51	0.49	32.00	10.00	21.00
1.2188	43.42	24.24	0.34	32.00	10.00	21.00
1.2604	43.26	24.33	0.49	32.00	10.00	21.00
1.3021	41.05	25.64	0.41	32.00	10.00	21.00
1.3438	41.68	25.25	0.38	32.00	10.00	21.00
1.3854	41.68	25.25	0.37	32.00	10.00	21.00
1.4583	41.05	25.64	0.37	32.00	10.00	21.00
1.9479	41.05	25.64	0.29	32.00	10.00	21.00
1.9931	42.09	25.01	0.39	32.00	10.00	21.00

2.0347	41.68	25.25	0.36	32.00	10.00	21.00
2.0938	41.84	25.16	0.45	32.00	9.50	20.75
2.1771	42.63	24.69	0.26	33.00	9.50	21.25
2.2188	41.84	25.16	0.41	33.00	9.50	21.25
2.2604	41.84	25.16	0.30	33.00	9.50	21.25
2.3021	41.84	25.16	0.36	33.00	9.50	21.25
2.3438	41.84	25.16	0.33	33.00	9.50	21.25
2.3854	42.63	24.69	0.32	33.00	9.50	21.25
2.9688	39.47	26.67	0.25	33.00	9.50	21.25
3.0104	39.47	26.67	0.28	33.00	9.50	21.25
3.0521	39.47	26.67	0.33	33.00	9.50	21.25
3.1042	39.47	26.67	0.25	33.00	9.50	21.25
3.1458	38.84	27.10	0.29	33.00	9.50	21.25
3.1875	39.47	26.67	0.26	33.00	9.50	21.25
3.2188	38.34	27.46	0.30	33.00	9.50	21.25
3.2604	39.47	26.67	0.27	33.00	9.50	21.25
3.3125	39.47	26.67	0.30	33.00	9.50	21.25
3.3438	38.84	27.10	0.26	33.00	9.50	21.25
3.3854	39.47	26.67	0.24	33.00	9.50	21.25
3.9583	36.51	28.84	0.26	32.00	9.25	20.63
4.0000	36.32	28.99	0.30	32.00	9.25	20.63
4.0417	35.68	29.50	0.27	32.00	9.25	20.63
4.0833	35.37	29.76	0.30	32.00	9.25	20.63
4.1250	36.32	28.99	0.35	32.00	9.25	20.63
4.1771	36.00	29.24	0.27	32.00	9.25	20.63
4.2188	35.53	29.63	0.30	32.00	9.25	20.63
4.2604	35.53	29.63	0.27	32.00	9.25	20.63
4.3021	35.68	29.50	0.31	32.00	9.25	20.63
4.3438	36.32	28.99	0.36	32.00	9.25	20.63
4.3854	35.53	29.63		32.00	9.25	20.63
4.9583	35.18	29.92	0.24	32.00	9.00	20.50
5.0000	35.53	29.63	0.35	32.00	9.00	20.50
5.0417	34.74	30.30	0.29	32.00	9.00	20.50
5.0938	34.74	30.30	0.39	32.00	9.00	20.50
5.4479	34.20	30.78	0.35	32.00	9.00	20.50
5.4688	34.74	30.30	0.34	32.00	9.00	20.50
5.4896	34.42	30.58	0.33	32.00	9.00	20.50
5.5313	34.74	30.30	0.35	32.00	9.00	20.50
5.5729	34.29	30.69	0.37	32.00	9.00	20.50
5.6354	34.74	30.30	0.35	32.00	9.00	20.50
6.1979	32.37	32.52	0.29	32.00	9.00	20.50
6.2396	32.27	32.62	0.30	32.00	9.00	20.50
6.2917	32.27	32.62	0.26	32.00	9.00	20.50
6.3438	32.27	32.62	0.26	32.00	9.00	20.50
6.3854	32.37	32.52	0.24	32.00	9.00	20.50

6.4688	32.37	32.52	0.28	32.00	9.00	20.50
6.5104	32.37	32.52	0.31	32.00	9.00	20.50
6.5521	32.21	32.68		32.00	9.00	20.50
6.5938	32.37	32.52	0.25	32.00	9.00	20.50
6.6354	29.21	36.04	0.30	32.00	9.00	20.50
7.1979	29.37	35.84	0.42	31.00	8.75	19.88
7.2396	30.79	34.19		31.00	8.75	19.88
7.2604	30.79	34.19		31.00	8.75	19.88
7.3021	30.88	34.08	0.28	31.00	8.75	19.88
7.3750	30.79	34.19	0.32	31.00	8.75	19.88
7.4167	30.79	34.19	0.30	31.00	8.75	19.88
7.5417	30.79	34.19	0.35	31.00	8.75	19.88
7.5729	30.95	34.01		31.00	8.75	19.88
7.6146	30.79	34.19	0.36	31.00	8.75	19.88
7.6563	30.79	34.19	0.24	31.00	8.75	19.88
7.6979	30.79	34.19	0.23	31.00	8.75	19.88
8.1979	30.00	35.09	0.30	31.00	8.75	19.88
8.2396	30.00	35.09	0.27	31.00	8.75	19.88
8.3021	30.00	35.09	0.23	31.00	8.75	19.88
8.3646	30.00	35.09	0.22	31.00	8.75	19.88
8.4063	30.00	35.09	0.30	31.00	8.75	19.88
8.4688	30.00	35.09	0.28	31.00	8.75	19.88
8.5208	30.00	35.09	0.25	31.00	8.75	19.88
8.5521	30.00	35.09	0.33	31.00	8.75	19.88
8.5938	30.00	35.09	0.30	31.00	8.75	19.88
8.6354	29.56	35.61	0.29	31.00	8.75	19.88
9.1979	29.21	36.04	0.40	31.00	8.50	19.75
9.2396	29.21	36.04	0.33	31.00	8.50	19.75
9.2813	29.21	36.04	0.24	31.00	8.50	19.75
9.3542	29.21	36.04	0.22	31.00	8.50	19.75
9.4063	29.21	36.04		31.00	8.50	19.75
9.4792	30.00	35.09	0.33	31.00	8.50	19.75
9.5417	29.87	35.24	0.21	31.00	8.50	19.75
9.5833	29.56	35.61	0.26	31.00	8.50	19.75
9.6250	29.21	36.04	0.24	31.00	8.50	19.75
9.6667	29.21	36.04	0.23	31.00	8.50	19.75
10.1979	28.42	37.04	0.33	30.00	8.50	19.25
10.2396	29.21	36.04	0.31	30.00	8.50	19.25
10.3021	28.42	37.04	0.24	30.00	8.50	19.25
10.3854	29.21	36.04	0.29	30.00	8.50	19.25
10.4375	29.21	36.04	0.27	30.00	8.50	19.25
10.4688	29.21	36.04	0.35	30.00	8.50	19.25
10.5208	29.05	36.23	0.36	30.00	8.50	19.25
10.5625	29.21	36.04	0.25	30.00	8.50	19.25
10.6042	29.21	36.04	0.30	30.00	8.50	19.25

10.6563	29.21	36.04	0.28	30.00	8.50	19.25
11.1979	28.42	37.04	0.28	31.00	8.25	19.63
11.2604	27.63	38.10	0.30	31.00	8.25	19.63
11.3021	27.63	38.10	0.25	31.00	8.25	19.63
11.3438	28.42	37.04	0.24	31.00	8.25	19.63
11.3854	28.42	37.04	0.26	31.00	8.25	19.63
11.4063	28.42	37.04	0.29	31.00	8.25	19.63
11.4479	28.42	37.04	0.27	31.00	8.25	19.63
11.4896	28.42	37.04	0.36	31.00	8.25	19.63
11.5313	28.42	37.04	0.39	31.00	8.25	19.63
11.5938	28.42	37.04	0.38	31.00	8.25	19.63
12.1979	27.63	38.10	0.35	30.00	8.50	19.25
12.2188	27.63	38.10	0.39	30.00	8.50	19.25
12.2188	116.84	9.01		30.00	8.50	19.25
12.2222	110.15	9.56	0.39	30.00	8.50	19.25
12.2257	109.64	9.60	0.33	30.00	8.50	19.25
12.2292	109.64	9.60	0.28	30.00	8.50	19.25
12.2361	109.64	9.60	0.40	30.00	8.50	19.25
12.2431	113.87	9.24	0.28	30.00	8.50	19.25
12.2500	113.68	9.26	0.32	30.00	8.50	19.25
12.2569	113.68	9.26	0.37	30.00	8.50	19.25
12.2639	116.84	9.01	0.31	30.00	8.50	19.25
12.2743	118.42	8.89	0.25	30.00	8.50	19.25
12.2847	118.42	8.89	0.38	30.00	8.50	19.25
12.3056	121.58	8.66	0.27	30.00	8.50	19.25
12.3264	122.53	8.59	0.29	30.00	8.50	19.25
12.3472	123.16	8.55	0.25	30.00	8.50	19.25
12.3576	121.58	8.66	0.27	30.00	8.50	19.25
12.5868	116.84	9.01	0.31	30.00	8.50	19.25
12.7639	112.11	9.39	0.29	30.00	8.50	19.25
12.8056	110.53	9.52	0.34	30.00	8.50	19.25
12.8889	110.53	9.52	0.30	30.00	8.50	19.25
12.9306	110.53	9.52		30.00	8.50	19.25
12.9722	110.53	9.52	0.32	30.00	8.50	19.25
13.0243	107.37	9.80	0.34	30.00	8.50	19.25
13.1076	105.79	9.95	0.35	30.00	8.50	19.25
13.1597	107.37	9.80	0.33	30.00	8.50	19.25
13.2014	105.79	9.95	0.34	30.00	8.50	19.25
13.2431	102.63	10.26		30.00	8.50	19.25
13.2951	97.89	10.75	0.36	30.00	8.50	19.25
13.3160	96.32	10.93	0.40	30.00	8.50	19.25
16.0035	86.84	12.12	0.29	30.00	8.50	19.25
16.0451	83.68	12.58	0.40	30.00	8.50	19.25
16.0938	85.26	12.35	0.36	30.00	8.50	19.25
16.1181	86.84	12.12	0.34	30.00	8.50	19.25

16.7118	80.53	13.07		30.00	9.75	19.88
16.7535	82.11	12.82		30.00	9.75	19.88
16.7743	83.68	12.58	0.37	30.00	9.75	19.88
16.8472	83.68	12.58	0.36	30.00	9.75	19.88
16.8993	85.26	12.35	0.37	30.00	9.75	19.88
16.9236	85.26	12.35	0.32	30.00	9.75	19.88
16.9826	85.26	12.35	0.33	30.00	9.75	19.88
17.0243	85.26	12.35	0.26	30.00	9.75	19.88
17.1076	85.26	12.35		30.00	9.75	19.88
17.1285	83.68	12.58		30.00	9.75	19.88
17.3264	85.26	12.35	0.39	30.00	9.75	19.88
17.7465	80.53	13.07	0.30	30.00	9.75	19.88
17.7882	82.11	12.82	0.30	30.00	9.75	19.88
17.8368	83.68	12.58	0.26	30.00	9.75	19.88
17.8785	82.11	12.82	0.23	30.00	9.75	19.88
17.9201	82.11	12.82	0.36	30.00	9.75	19.88
18.0035	82.11	12.82	0.31	30.00	9.75	19.88
18.0660	83.68	12.58	0.29	30.00	9.75	19.88
18.1076	85.26	12.35		30.00	9.75	19.88
18.1389	83.68	12.58		30.00	9.75	19.88
18.7049	85.26	12.35	0.34	29.00	9.50	19.25
18.7639	85.26	12.35	0.29	29.00	9.50	19.25
18.7951	83.68	12.58	0.26	29.00	9.50	19.25
18.8368	82.11	12.82	0.25	29.00	9.50	19.25
18.9201	83.68	12.58	0.27	29.00	9.50	19.25
18.9618	82.11	12.82	0.22	29.00	9.50	19.25
19.0035	82.11	12.82	0.26	29.00	9.50	19.25
19.0451	83.68	12.58	0.41	29.00	9.50	19.25
19.1285	83.68	12.58	0.31	29.00	9.50	19.25
19.7118	83.68	12.58	0.28	29.00	9.50	19.25
19.7639	83.68	12.58	0.32	29.00	9.50	19.25
19.8472	83.68	12.58	0.34	29.00	9.50	19.25
19.9097	83.68	12.58	0.31	29.00	9.50	19.25
19.9722	83.68	12.58		29.00	9.50	19.25
20.0868	83.68	12.58	0.28	29.00	9.50	19.25
20.1285	82.11	12.82	0.38	29.00	9.50	19.25
20.7118	83.68	12.58	0.43	29.00	9.50	19.25
20.7535	80.53	13.07	0.39	29.00	9.50	19.25
20.7847	80.53	13.07	0.33	29.00	9.50	19.25
20.8472	82.11	12.82	0.39	29.00	9.50	19.25
20.9826	80.53	13.07	0.44	29.00	9.50	19.25
21.0556	77.37	13.61	0.34	29.00	9.50	19.25
21.0868	78.95	13.33		29.00	9.50	19.25
21.1285	78.95	13.33	0.34	29.00	9.50	19.25
21.7083	77.37	13.61	0.33	29.00	9.50	19.25

21.7639	77.37	13.61	0.31	29.00	9.50	19.25
21.8576	77.37	13.61	0.40	29.00	9.50	19.25
21.9201	75.79	13.89	0.35	29.00	9.50	19.25
21.9931	77.37	13.61	0.38	29.00	9.50	19.25
22.0556	77.37	13.61	0.26	29.00	9.50	19.25
22.1076	78.95	13.33	0.30	29.00	9.50	19.25
22.7083	75.79	13.89	0.38	28.00	9.25	18.63
22.7535	75.79	13.89	0.33	28.00	9.25	18.63
22.7743	75.79	13.89	0.39	28.00	9.25	18.63
22.8576	74.21	14.18	0.26	28.00	9.25	18.63
22.8993	74.21	14.18	0.37	28.00	9.25	18.63
23.0035	74.21	14.18		28.00	9.25	18.63
23.0868	74.21	14.18		28.00	9.25	18.63
23.1285	72.76	14.47	0.31	28.00	9.25	18.63
23.7118	74.21	14.18	0.37	28.00	9.25	18.63
23.7431	74.21	14.18	0.30	28.00	9.25	18.63
23.7743	74.21	14.18	0.33	28.00	9.25	18.63
23.8576	74.21	14.18	0.30	28.00	9.25	18.63
23.9097	74.21	14.18	0.37	28.00	9.25	18.63
23.9306	74.21	14.18		28.00	9.25	18.63
23.9514	74.21	14.18	0.42	28.00	9.25	18.63
23.9931	72.63	14.49	0.29	28.00	9.25	18.63
24.0868	72.63	14.49	0.32	28.00	9.25	18.63
24.1285	74.21	14.18	0.31	28.00	9.25	18.63
24.7535	72.63	14.49		28.00	9.25	18.63
24.8368	72.63	14.49		28.00	9.25	18.63
24.8576	72.63	14.49	0.41	28.00	9.25	18.63
24.9097	72.63	14.49	0.28	28.00	9.25	18.63
24.9410	72.63	14.49	0.39	28.00	9.25	18.63
24.9931	72.63	14.49	0.41	28.00	9.25	18.63
25.0347	72.63	14.49	0.35	28.00	9.25	18.63
25.0764	72.63	14.49	0.22	28.00	9.25	18.63
25.1493	72.63	14.49		28.00	9.25	18.63
25.1701	72.63	14.49		28.00	9.25	18.63
25.5347	72.63	14.49		28.00	9.25	18.63
25.5556	63.16	16.67	0.27	28.00	9.25	18.63
25.5868	63.16	16.67	0.38	28.00	9.25	18.63
25.6076	63.16	16.67	0.33	28.00	9.25	18.63
25.6389	64.74	16.26	0.44	28.00	9.25	18.63
26.1910	61.58	17.09	0.41	28.00	9.25	18.63
26.2326	63.16	16.67	0.39	28.00	9.25	18.63
26.3264	63.16	16.67	0.36	28.00	9.25	18.63
26.3576	64.74	16.26	0.39	28.00	9.25	18.63
26.3993	63.16	16.67	0.42	28.00	9.25	18.63
26.4514	64.74	16.26	0.38	28.00	9.25	18.63

26.4618	64.20	16.40	0.4	28.00	9.25	18.63
26.5035	64.74	16.26	0.41	28.00	9.25	18.63
26.5451	66.32	15.87	0.48	28.00	9.25	18.63
26.6285	66.32	15.87	0.41	28.00	9.25	18.63
27.1979	61.58	17.09		28.00	9.25	18.63
27.2292	63.16	16.67	0.37	28.00	9.25	18.63
27.2535	63.16	16.67	0.41	28.00	9.25	18.63
27.3160	63.16	16.67	0.42	28.00	9.25	18.63
27.3576	64.74	16.26	0.4	28.00	9.25	18.63
27.4201	64.74	16.26	0.45	28.00	9.25	18.63
27.4722	64.74	16.26	0.42	28.00	9.25	18.63
27.5035	64.74	16.26	0.42	28.00	9.25	18.63
27.5660	64.74	16.26	0.38	28.00	9.25	18.63
28.1910	63.16	16.67	0.48	29.00	9.25	19.13
28.2535	63.16	16.67	0.39	29.00	9.25	19.13
28.3264	63.16	16.67	0.41	29.00	9.25	19.13
28.4097	62.12	16.95	0.46	29.00	9.25	19.13
28.4514	61.58	17.09	0.44	29.00	9.25	19.13
28.4931	61.58	17.09		29.00	9.25	19.13
28.5451	61.58	17.09	0.33	29.00	9.25	19.13
28.5868	61.58	17.09	0.4	29.00	9.25	19.13
29.2014	58.42	18.02	0.49	29.00	9.00	19.00
29.2257	58.42	18.02	0.42	29.00	9.00	19.00
29.2535	58.42	18.02	0.34	29.00	9.00	19.00
29.3264	56.84	18.52	0.37	29.00	9.00	19.00
29.3889	56.84	18.52	0.41	29.00	9.00	19.00
29.4201	56.84	18.52	0.38	29.00	9.00	19.00
29.4757	56.75	18.55	0.36	29.00	9.00	19.00
29.5243	56.84	18.52	0.36	29.00	9.00	19.00
29.5451	56.84	18.52	0.37	29.00	9.00	19.00
29.5972	56.84	18.52	0.39	29.00	9.00	19.00
30.2431	53.68	19.61	0.44	29.00	9.25	19.13
30.2986	53.68	19.61	0.41	29.00	9.25	19.13
30.3368	53.68	19.61	0.36	29.00	9.25	19.13
30.3924	53.68	19.61	0.37	29.00	9.25	19.13
30.4271	53.68	19.61	0.36	29.00	9.25	19.13
30.4826	52.64	20.00	0.49	29.00	9.25	19.13
30.5451	53.68	19.61	0.34	29.00	9.25	19.13
30.5868	53.68	19.61	0.39	29.00	9.25	19.13
31.2153	52.11	20.20	0.39	29.00	9.25	19.13
31.2326	52.11	20.20	0.36	29.00	9.25	19.13
31.2535	52.11	20.20	0.39	29.00	9.25	19.13
31.2847	52.11	20.20	0.4	29.00	9.25	19.13
31.3819	52.11	20.20	0.39	29.00	9.25	19.13
31.4201	52.11	20.20	0.4	29.00	9.25	19.13

31.4618	52.11	20.20	0.39	29.00	9.25	19.13
31.5035	52.11	20.20	0.35	29.00	9.25	19.13
31.5625	53.68	19.61	0.34	29.00	9.25	19.13
31.5868	52.11	20.20	0.38	29.00	9.25	19.13
32.1944	53.68	19.61	0.39	27.00	9.00	18.00
32.2569	52.11	20.20	0.38	27.00	9.00	18.00
32.3299	52.11	20.20	0.36	27.00	9.00	18.00
32.3889	52.11	20.20	0.42	27.00	9.00	18.00
32.4444	52.11	20.20	0.36	27.00	9.00	18.00
32.4722	52.11	20.20	0.41	27.00	9.00	18.00
32.5069	52.11	20.20	0.36	27.00	9.00	18.00
32.5486	52.11	20.20	0.36	27.00	9.00	18.00
32.6111	52.11	20.20	0.41	27.00	9.00	18.00
33.1944	52.64	20.00	0.38	27.00	9.00	18.00
33.2569	52.11	20.20	0.4	27.00	9.00	18.00
33.3403	52.11	20.20	0.41	27.00	9.00	18.00
33.4236	52.11	20.20	0.41	27.00	9.00	18.00
33.4757	52.11	20.20	0.44	27.00	9.00	18.00
33.5069	52.64	20.00	0.39	27.00	9.00	18.00
33.6007	52.11	20.20	0.43	27.00	9.00	18.00
34.1944	52.11	20.20	0.48	27.00	9.00	18.00
34.2569	52.11	20.20	0.41	27.00	9.00	18.00
34.3299	52.11	20.20	0.37	27.00	9.00	18.00
34.4132	52.11	20.20	0.35	27.00	9.00	18.00
34.4757	52.11	20.20	0.4	27.00	9.00	18.00
34.5174	53.68	19.61	0.38	27.00	9.00	18.00
34.5556	53.68	19.61	0.37	27.00	9.00	18.00
34.6111	52.11	20.20	0.4	27.00	9.00	18.00
35.1944	52.11	20.20	0.42	27.00	9.00	18.00
35.2361	50.53	20.83	0.4	27.00	9.00	18.00
35.2569	50.53	20.83	0.41	27.00	9.00	18.00
35.3403	50.53	20.83	0.4	27.00	9.00	18.00
35.3854	50.53	20.83	0.39	27.00	9.00	18.00
35.4688	48.95	21.51	0.4	27.00	9.00	18.00
35.5174	48.95	21.51	0.35	27.00	9.00	18.00
35.5486	48.95	21.51	0.36	27.00	9.00	18.00
35.5903	48.41	21.74	0.4	27.00	9.00	18.00
36.1944	46.01	22.88	0.43	26.00	8.50	17.25
36.2153	48.00	21.93	0.4	26.00	8.50	17.25
36.2569	47.37	22.22	0.41	26.00	8.50	17.25
36.3299	46.33	22.72	0.37	26.00	8.50	17.25
36.3854	46.58	22.60	0.38	26.00	8.50	17.25
36.4132	46.33	22.72	0.4	26.00	8.50	17.25
36.4688	47.37	22.22	0.39	26.00	8.50	17.25
36.6111	46.33	22.72	0.41	26.00	8.50	17.25

37.2361	45.25	23.26	0.43	27.00	9.00	18.00
37.2778	46.33	22.72	0.38	27.00	9.00	18.00
37.3090	47.37	22.22	0.4	27.00	9.00	18.00
37.3403	46.33	22.72	0.4	27.00	9.00	18.00
37.3854	46.33	22.72	0.39	27.00	9.00	18.00
37.4236	46.33	22.72	0.46	27.00	9.00	18.00
37.4688	47.37	22.22	0.39	27.00	9.00	18.00
37.5278	47.37	22.22	0.39	27.00	9.00	18.00
37.5799	47.37	22.22	0.42	27.00	9.00	18.00
38.2257	43.17	24.38	0.42	26.00	8.50	17.25
38.2569	43.17	24.38	0.39	26.00	8.50	17.25
38.3021	42.09	25.01	0.35	26.00	8.50	17.25
38.3264	42.09	25.01	0.35	26.00	8.50	17.25
38.6389	42.09	25.01	0.36	26.00	8.50	17.25
38.6632	42.09	25.01	0.4	26.00	8.50	17.25
39.1944	43.42	24.24	0.34	26.00	8.50	17.25
39.2153	42.09	25.01		26.00	8.50	17.25
39.2569	42.09	25.01	0.42	26.00	8.50	17.25
39.3403	42.09	25.01		26.00	8.50	17.25
39.3854	43.17	24.38	0.42	26.00	8.50	17.25
39.4688	43.17	24.38	0.39	26.00	8.50	17.25
39.5486	44.21	23.81	0.41	26.00	8.50	17.25
39.5903	44.21	23.81	0.49	26.00	8.50	17.25
40.1944	42.09	25.01	0.45	26.00	8.50	17.25
40.2569	44.21	23.81	0.49	26.00	8.50	17.25
40.3403	42.09	25.01		26.00	8.50	17.25
40.3854	42.09	25.01	0.44	26.00	8.50	17.25
40.4688	42.09	25.01	0.43	26.00	8.50	17.25
40.5069	42.09	25.01		26.00	8.50	17.25
40.5486	42.09	25.01	0.45	26.00	8.50	17.25
40.5903	42.09	25.01	0.47	26.00	8.50	17.25
41.1944	41.05	25.64	0.4	25.00	8.25	16.63
41.2153	42.09	25.01	0.4	25.00	8.25	16.63
41.2569	42.00	25.06	0.43	25.00	8.25	16.63
41.3299	44.21	23.81	0.39	26.00	8.50	17.25
41.3819	43.17	24.38	0.38	26.00	8.50	17.25
41.4757	43.17	24.38	0.46	26.00	8.50	17.25
41.5069	43.17	24.38	0.39	26.00	8.50	17.25
41.6007	43.17	24.38	0.47	26.00	8.50	17.25
42.1944	41.05	25.64	0.36	25.00	8.25	16.63
42.2257	42.09	25.01	0.4	25.00	8.25	16.63
42.3299	43.17	24.38	0.39	25.00	8.25	16.63
42.4132	43.17	24.38	0.41	26.00	8.25	17.13
42.4688	41.40	25.43	0.48	26.00	8.25	17.13
42.5069	41.05	25.64	0.5	25.00	8.00	16.50

42.5903	42.09	25.01		25.00	8.00	16.50
43.1944	42.09	25.01	0.49	25.00	8.00	16.50
43.2292	43.17	24.38	0.46	25.00	8.00	16.50
43.2986	43.17	24.38	0.35	25.00	8.00	16.50
43.4236	41.49	25.37	0.39	25.00	8.00	16.50
43.4688	41.49	25.37	0.39	25.00	8.00	16.50
43.5069	41.49	25.37	0.44	25.00	8.00	16.50
43.5486	41.49	25.37	0.49	25.00	8.00	16.50
43.6007	41.49	25.37	0.43	25.00	8.00	16.50
44.3403	40.01	26.31	0.43	24.00	7.50	15.75
44.3889	40.01	26.31	0.45	24.00	7.50	15.75
44.4132	41.05	25.64	0.39	24.00	7.50	15.75
44.4688	41.05	25.64	0.39	24.00	7.50	15.75
44.4896	41.05	25.64	0.41	24.00	7.50	15.75
44.5486	41.84	25.16	0.46	24.00	7.50	15.75
44.6215	42.09	25.01	0.42	24.00	7.50	15.75
45.2361	39.47	26.67	0.45	24.00	7.50	15.75
45.2674	40.26	26.14	0.4	24.00	7.50	15.75
45.3889	39.47	26.67	0.47	24.00	7.50	15.75
45.4132	40.26	26.14	0.39	24.00	7.50	15.75
45.4653	40.26	26.14	0.41	24.00	7.50	15.75
45.5486	40.26	26.14	0.39	24.00	7.50	15.75
46.1944	38.68	27.21	0.4	23.00	7.25	15.13
46.2431	38.68	27.21	0.39	23.00	7.25	15.13
46.3264	38.68	27.21	0.44	23.00	7.25	15.13
46.3889	38.68	27.21	0.41	23.00	7.25	15.13
46.4132	38.68	27.21	0.4	23.00	7.25	15.13
46.4688	39.28	26.80	0.5	23.00	7.25	15.13
46.5313	39.47	26.67	0.49	23.00	7.25	15.13
46.5625	39.47	26.67	0.53	23.00	7.25	15.13
47.2083	38.68	27.21	0.51	24.00	7.50	15.75
47.2396	41.05	25.64	0.5	24.00	7.50	15.75
47.2708	39.47	26.67	0.39	24.00	7.50	15.75
47.3438	39.47	26.67	0.48	24.00	7.50	15.75
47.4097	38.68	27.21	0.51	24.00	7.50	15.75
47.4271	38.68	27.21	0.52	24.00	7.50	15.75
47.4896	38.68	27.21	0.53	22.00	7.00	14.50
47.5625	38.68	27.21	0.4	22.00	7.00	14.50
48.2083	37.89	27.78	0.44	22.00	7.25	14.63
48.2326	34.74	30.30	0.48	22.00	7.25	14.63
48.2708	37.89	27.78	0.44	22.00	7.25	14.63
48.3542	37.11	28.37	0.5	22.00	7.25	14.63
48.4063	39.47	26.67	0.44	23.00	7.25	15.13
48.4271	38.68	27.21	0.39	23.00	7.25	15.13
48.4861	38.68	27.21	0.41	23.00	7.25	15.13

48.5625	38.68	27.21	0.39	23.00	7.25	15.13
49.2014	37.89	27.78	0.44	23.00	7.25	15.13
49.2361	38.59	27.28	0.48	23.00	7.25	15.13
49.2708	38.68	27.21	0.38	23.00	7.25	15.13
49.2951	39.47	26.67	0.39	23.00	7.25	15.13
49.3576	39.47	26.67	0.49	23.00	7.25	15.13
49.3854	39.47	26.67	0.45	23.00	7.25	15.13
49.4688	37.89	27.78	0.47	23.00	7.25	15.13
49.5208	38.68	27.21	0.45	23.00	7.25	15.13
50.1667	38.68	27.21	0.4	23.00	7.25	15.13
50.1910	39.47	26.67	0.4	23.00	7.25	15.13
50.2188	39.47	26.67	0.41	23.00	7.25	15.13
50.3056	40.26	26.14	0.43	23.00	7.25	15.13
50.3576	41.05	25.64	0.45	23.00	7.25	15.13
50.3889	39.47	26.67	0.49	23.00	7.25	15.13
50.4444	40.26	26.14	0.55	23.00	7.25	15.13
50.4931	40.26	26.14	0.45	23.00	7.25	15.13
51.2222	39.47	26.67	0.5	23.00	7.25	15.13
51.2535	37.36	28.18	0.45	23.00	7.25	15.13
51.2847	39.47	26.67	0.39	23.00	7.25	15.13
51.3299	39.47	26.67	0.49	23.00	7.25	15.13
51.3611	39.28	26.80	0.42	23.00	7.25	15.13
51.4306	39.47	26.67	0.49	23.00	7.25	15.13
51.4618	39.47	26.67	0.42	23.00	7.25	15.13
51.4931	39.47	26.67		22.00	7.00	14.50
52.2118	38.68	27.21	0.45	22.00	7.00	14.50
52.3472	38.53	27.32	0.54	22.00	7.00	14.50
52.3681	37.89	27.78	0.4	22.00	7.00	14.50
52.4132	38.68	27.21	0.4	22.00	7.00	14.50
52.4931	38.68	27.21	0.4	22.00	7.00	14.50
52.5347	37.89	27.78	0.47	22.00	7.00	14.50
53.1389	39.47	26.67	0.43	24.00	7.75	15.88
53.1632	41.84	25.16	0.43	24.00	7.75	15.88
53.1910	41.84	25.16	0.45	24.00	7.75	15.88
53.2743	42.63	24.69	0.38	24.00	7.75	15.88
53.3299	42.63	24.69	0.42	24.00	7.75	15.88
53.3576	42.63	24.69	0.44	24.00	7.75	15.88
53.4097	44.21	23.81	0.46	24.00	7.75	15.88
53.4931	44.21	23.81	0.47	24.00	7.75	15.88
53.5972	45.00	23.39	0.49	24.00	7.75	15.88
54.1389	42.09	25.01	0.4	24.00	7.75	15.88
54.1632	41.84	25.16	0.43	24.00	7.75	15.88
54.1910	41.84	25.16	0.43	24.00	7.75	15.88
54.2743	43.42	24.24	0.42	24.00	7.75	15.88
54.3542	44.21	23.81	0.42	24.00	7.75	15.88

54.4306	45.00	23.39	0.52	24.00	7.75	15.88
54.4931	45.00	23.39	0.48	24.00	7.75	15.88
54.5972	46.58	22.60	0.48	24.00	7.75	15.88
55.1389	45.79	22.99	0.43	24.00	7.75	15.88
55.1632	45.00	23.39	0.44	24.00	7.75	15.88
55.2014	45.00	23.39	0.46	24.00	7.75	15.88
55.2743	48.63	21.65	0.43	24.00	7.75	15.88
55.3299	45.79	22.99	0.43	24.00	7.75	15.88
55.3993	46.11	22.83	0.52	24.00	7.75	15.88
55.4931	46.58	22.60	0.48	24.00	7.75	15.88
56.1389	45.79	22.99	0.52	24.00	7.75	15.88
56.1632	45.79	22.99	0.55	24.00	7.75	15.88
56.1910	45.79	22.99	0.49	24.00	7.75	15.88
56.2743	45.79	22.99	0.45	24.00	7.75	15.88
56.3299	45.00	23.39	0.44	24.00	7.75	15.88
56.4132	45.00	23.39	0.46	24.00	7.75	15.88
56.4931	45.00	23.39	0.44	24.00	7.75	15.88
56.5556	45.79	22.99	0.52	24.00	7.75	15.88
56.8472	45.60	23.08	0.49	24.00	7.75	15.88
56.8785	46.58	22.60	0.46	24.00	7.75	15.88
56.9097	46.58	22.60	0.45	24.00	7.75	15.88
56.9410	46.58	22.60	0.49	24.00	7.75	15.88
56.9965	46.58	22.60	0.44	24.00	7.75	15.88
57.0243	46.58	22.60	0.56	24.00	7.75	15.88
57.1389	46.33	22.72	0.51	24.00	7.75	15.88
57.1806	47.37	22.22	0.51	24.00	7.75	15.88
57.8368	46.58	22.60	0.48	24.00	7.50	15.75
57.8576	46.58	22.60	0.47	24.00	7.50	15.75
57.9097	46.58	22.60	0.43	24.00	7.50	15.75
57.9410	47.37	22.22	0.43	24.00	7.50	15.75
58.0000	46.58	22.60	0.46	24.00	7.50	15.75
58.0243	46.58	22.60	0.47	24.00	7.50	15.75
58.1806	46.58	22.60	0.53	24.00	7.50	15.75
58.8576	47.37	22.22	0.51	24.00	7.50	15.75
59.0139	47.37	22.22	0.57	24.00	7.50	15.75
59.0243	48.16	21.86	0.52	24.00	7.50	15.75
59.0764	47.37	22.22	0.55	24.00	7.50	15.75
59.1285	48.16	21.86	0.52	24.00	7.50	15.75
59.8056	47.72	22.06		23.00	7.25	15.13
59.8576	45.79	22.99		23.00	7.25	15.13
59.9340	45.60	23.08		23.00	7.25	15.13
59.9965	45.79	22.99		23.00	7.25	15.13
60.0243	46.58	22.60		23.00	7.25	15.13
60.1597	47.37	22.22		23.00	7.25	15.13
60.8056	45.79	22.99		23.00	7.25	15.13

60.8681	45.79	22.99		23.00	7.25	15.13
60.9410	45.00	23.39		22.00	7.25	14.63
61.0417	22.11	47.62		22.00	7.00	14.50
61.0764	17.37	60.61		22.00	7.00	14.50
61.0764	122.97	8.56		24.00	8.50	16.25
61.0833	112.11	9.39		25.00	8.25	16.63
61.0903	110.53	9.52		24.00	8.00	16.00
61.0972	112.11	9.39		24.00	8.00	16.00
61.1076	113.68	9.26		24.00	8.00	16.00
61.1250	110.53	9.52		24.00	8.00	16.00
61.1354	110.53	9.52		23.00	7.50	15.25
61.1528	107.37	9.80		23.00	7.50	15.25
61.1736	104.21	10.10		23.00	7.50	15.25
61.2049	94.74	11.11		23.00	7.50	15.25
61.2257	91.58	11.49		22.00	7.50	14.75
61.2465	88.42	11.90		22.00	7.50	14.75
61.2778	85.26	12.35		22.00	7.50	14.75
61.3090	83.49	12.61		22.00	7.50	14.75
61.4028	74.21	14.18		22.00	7.50	14.75
61.9653	69.47	15.15		22.00	7.25	14.63
61.9861	70.52	14.93		22.00	7.25	14.63
62.0069	70.52	14.93		22.00	7.25	14.63
62.0486	70.52	14.93		22.00	7.25	14.63
62.1528	71.59	14.70		22.00	7.25	14.63
62.1736	71.59	14.70		22.00	7.25	14.63
62.2569	71.59	14.70		22.00	7.25	14.63
62.3090	72.63	14.49		22.00	7.25	14.63
62.9549	73.67	14.29		22.00	7.25	14.63
62.9826	74.21	14.18		22.00	7.25	14.63
63.0174	74.84	14.06		22.00	7.25	14.63
63.0903	72.63	14.49		22.00	7.25	14.63
63.1458	72.63	14.49		22.00	7.25	14.63
63.1840	72.63	14.49		22.00	7.25	14.63
63.2292	73.67	14.29		22.00	7.25	14.63
63.3090	73.67	14.29		22.00	7.25	14.63
63.9549	68.43	15.38		22.00	7.00	14.50
63.9792	67.36	15.63		22.00	7.00	14.50
63.9965	67.36	15.63		22.00	7.00	14.50
64.0174	67.36	15.63		22.00	7.00	14.50
64.0903	66.32	15.87		22.00	7.00	14.50
64.1424	65.27	16.13		22.00	7.00	14.50
64.1701	66.32	15.87		22.00	7.00	14.50
64.3924	66.32	15.87		22.00	7.00	14.50

64.3924	126.00	10.58		23.00	8.00	15.50
64.3958	124.00	10.75		23.00	8.00	15.50
64.3993	122.00	10.93		23.00	8.00	15.50
64.4063	126.00	10.58		23.00	8.00	15.50
64.4132	128.00	10.42		23.00	8.00	15.50
64.4236	132.00	10.10		23.00	8.00	15.50
64.4340	136.00	9.80		23.00	8.00	15.50
64.4444	138.00	9.66		22.00	7.25	14.63
64.4549	140.00	9.52		22.00	7.25	14.63
64.5556	140.00	9.52		21.00	7.00	14.00
64.5799	140.00	9.52		21.00	7.00	14.00
64.6181	138.00	9.66		21.00	7.00	14.00
64.6736	136.00	9.80		21.00	7.00	14.00
64.7361	134.00	9.95		21.00	7.00	14.00
64.7986	134.00	9.95		21.00	7.00	14.00
65.3542	138.00	9.66		20.00	6.75	13.38
65.4375	134.00	9.95		20.00	6.75	13.38
65.4965	136.00	9.80		20.00	6.75	13.38
65.5625	132.00	10.10		20.00	6.75	13.38
65.6910	90.00	14.81		20.00	6.75	13.38
68.3611	90.68	14.70		20.00	6.75	13.38
69.7569	92.00	14.49		20.00	7.00	13.50
70.3958	90.68	14.70		21.00	6.75	13.88
70.4236	86.68	15.38		21.00	6.75	13.88
70.4549	87.40	15.26		21.00	6.75	13.88
70.5625	88.00	15.15		21.00	6.75	13.88
70.6528	88.00	15.15		21.00	6.75	13.88
70.7361	86.68	15.38		21.00	6.75	13.88
71.3611	86.68	15.38		21.00	6.50	13.75
71.3924	84.00	15.87		21.00	6.50	13.75
71.5069	86.68	15.38		21.00	6.50	13.75
71.5625	85.32	15.63		21.00	6.50	13.75
71.7049	86.68	15.38		21.00	6.50	13.75
72.3611	84.00	15.87		20.00	6.75	13.38
72.3889	84.00	15.87		20.00	6.75	13.38
72.5069	82.00	16.26		20.00	6.75	13.38
72.6424	81.32	16.40		20.00	6.75	13.38
72.7986	82.68	16.13		20.00	6.75	13.38
73.3611	81.32	16.40		20.00	6.50	13.25
73.3854	81.32	16.40		20.00	7.50	13.75
73.5069	82.68	16.13		20.00	8.50	14.25
73.5521	80.00	16.67		19.00	6.50	12.75

73.5764	80.00	16.67		19.00	6.50	12.75
73.7361	80.00	16.67		19.00	6.25	12.63
74.5069	78.68	16.95		19.00	6.50	12.75
74.5764	78.68	16.95		19.00	6.50	12.75
74.7569	80.00	16.67		19.00	6.50	12.75
75.3715	73.32	18.19		18.00	6.00	12.00
75.3889	76.00	17.54		18.00	6.00	12.00
75.4340	77.32	17.24		18.00	6.00	12.00
75.4931	76.00	17.54		18.00	6.00	12.00
75.5694	77.32	17.24		18.00	6.00	12.00
75.7153	76.00	17.54		18.00	6.00	12.00
76.3889	82.68	16.13		20.00	6.75	13.38
76.4028	84.00	15.87		20.00	6.75	13.38
76.4861	82.68	16.13		20.00	6.75	13.38
76.5556	85.32	15.63		20.00	6.75	13.38
76.6215	85.32	15.63		20.00	6.75	13.38
76.7153	86.68	15.38		20.00	6.75	13.38
77.3750	84.00	15.87		20.00	6.75	13.38
77.3854	84.00	15.87		20.00	6.75	13.38
77.3958	82.68	16.13		20.00	6.75	13.38
77.4549	82.68	16.13		20.00	6.75	13.38
77.5556	82.68	16.13		20.00	6.75	13.38
77.7049	81.32	16.40		20.00	6.75	13.38
78.3611	54.68	24.38		19.00	6.50	12.75
78.3854	56.00	23.81		19.00	6.50	12.75
78.4028	54.68	24.38		19.00	6.50	12.75
78.4792	54.68	24.38		19.00	6.50	12.75
78.5660	53.32	25.01		19.00	6.50	12.75
78.6771	52.00	25.64		19.00	6.50	12.75
78.7188	53.32	25.01		19.00	6.50	12.75
79.3681	50.68	26.31		19.00	6.13	12.56
79.3924	50.68	26.31		19.00	6.13	12.56
79.4028	50.68	26.31		19.00	6.13	12.56
79.4931	50.68	26.31		19.00	6.13	12.56
79.5833	50.68	26.31		19.00	6.13	12.56
79.7188	52.00	25.64		19.00	6.13	12.56
80.3646	50.68	26.31		19.00	6.50	12.75
80.3896	50.68	26.31		19.00	6.50	12.75
80.4167	50.68	26.31		19.00	6.50	12.75
80.4931	52.00	25.64		19.00	6.50	12.75
80.6667	50.68	26.31		19.00	6.50	12.75
80.6979	50.68	26.31		19.00	6.50	12.75
81.3507	48.00	27.78		19.00	6.25	12.63
81.3958	46.68	28.56		19.00	6.25	12.63
81.4167	46.80	28.49		19.00	6.25	12.63

81.5104	46.68	28.56		19.00	6.25	12.63
81.6667	44.00	30.30		18.00	6.25	12.13
81.7326	42.68	31.24		18.00	6.25	12.13
82.3681	44.00	30.30		18.00	6.25	12.13
82.3958	44.00	30.30		18.00	6.25	12.13
82.4097	44.00	30.30		18.00	6.25	12.13
82.4965	44.00	30.30		18.00	6.25	12.13
82.7083	42.68	31.24		18.00	6.25	12.13
82.7083	100.00	13.33		20.00	7.25	13.63
82.7153	100.00	13.33		19.00	7.00	13.00
82.7292	94.00	14.18		19.00	6.75	12.88
82.7465	102.00	13.07		19.00	6.75	12.88
82.7986	112.00	11.90		19.00	6.75	12.88
82.8403	113.76	11.72		19.00	6.75	12.88
82.8715	114.00	11.70		19.00	6.75	12.88
82.9132	106.00	12.58		17.00	6.00	11.50
82.9861	106.00	12.58		17.00	6.25	11.63
83.0278	106.00	12.58		17.00	6.25	11.63
83.6632	98.00	13.61		17.00	6.00	11.50
83.6910	100.00	13.33		17.00	6.00	11.50
83.7153	100.00	13.33		17.00	6.25	11.63
83.8090	98.00	13.61		17.00	6.25	11.63
83.8576	98.00	13.61		17.00	6.25	11.63
83.9549	96.00	13.89		17.00	6.25	11.63
84.0174	98.00	13.61		17.00	6.25	11.63
84.6632	98.00	13.61		17.00	6.25	11.63
84.7257	96.00	13.89		17.00	6.25	11.63
84.7882	94.00	14.18		17.00	6.25	11.63
84.8576	94.00	14.18		17.00	6.25	11.63
84.9549	92.00	14.49		17.00	6.25	11.63
85.0382	94.00	14.18		17.00	6.25	11.63
85.0799	94.40	14.12		17.00	6.25	11.63
85.6632	92.00	14.49		17.00	6.00	11.50
85.7882	92.00	14.49		17.00	6.00	11.50
85.8750	92.00	14.49		17.00	6.00	11.50
85.9618	90.00	14.81		17.00	6.00	11.50
86.0278	88.00	15.15		17.00	6.00	11.50
86.5799	86.00	15.50		17.00	6.00	11.50
86.7257	86.00	15.50		17.00	6.00	11.50
86.8299	84.00	15.87		17.00	6.00	11.50
86.8854	84.00	15.87		17.00	6.00	11.50
86.9514	84.00	15.87		17.00	6.00	11.50
86.9653	82.00	16.26		17.00	6.00	11.50
87.0174	84.00	15.87		17.00	6.00	11.50
87.7257	82.00	16.26		17.00	6.00	11.50

87.7951	82.00	16.26		17.00	6.00	11.50
87.8715	82.00	16.26		17.00	6.00	11.50
87.9410	82.00	16.26		17.00	6.00	11.50
88.0174	82.00	16.26		17.00	6.00	11.50
88.7326	80.00	16.67		17.00	6.00	11.50
88.8750	78.00	17.09		17.00	6.00	11.50
88.9444	78.00	17.09		17.00	6.00	11.50
88.9861	78.00	17.09		17.00	6.00	11.50
89.0278	78.00	17.09		17.00	6.00	11.50
89.6632	78.00	17.09		17.00	6.00	11.50
89.7361	76.00	17.54		17.00	6.00	11.50
89.7882	76.00	17.54		17.00	6.00	11.50
89.9444	72.00	18.52		17.00	6.00	11.50
89.9757	74.00	18.02		17.00	6.00	11.50
90.0278	72.00	18.52		17.00	6.00	11.50
90.6667	70.00	19.05		17.00	6.00	11.50
90.6979	68.00	19.61		17.00	6.00	11.50
90.8160	70.00	19.05		17.00	6.00	11.50
90.8819	70.00	19.05		17.00	6.00	11.50
91.0278	73.60	18.12		17.00	6.00	11.50
91.6667	66.00	20.20		17.00	6.00	11.50
91.7049	68.00	19.61		17.00	6.00	11.50
91.7882	68.00	19.61		17.00	6.00	11.50
91.8715	70.00	19.05		17.00	6.00	11.50
91.8924	70.00	19.05		17.00	6.00	11.50

APPENDIX D

RAW DATA FOR DETERMINING EFFECT OF HRT ON THE CF-MBR PERFORMANCE

Table D1: Hydraulic performance data at different Crossflow Velocity (CFV) at MLSS 5000 mg/L

a) At CFV = 3.24 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	81.60	16.34	15.00	5.50	10.25
0.08	80.00	16.67	15.00	5.50	10.25
0.25	80.00	16.67	15.00	5.25	10.13
0.50	82.00	16.26	15.00	5.25	10.13
0.75	82.00	16.26	15.00	5.25	10.13
1.00	86.00	15.50	15.00	5.25	10.13
2.75	90.48	14.74	15.00	5.25	10.13
3.00	88.00	15.15	15.00	5.00	10.00
3.67	90.00	14.81	15.00	5.00	10.00
4.25	88.00	15.15	15.00	5.00	10.00
5.00	86.00	15.50	15.00	5.00	10.00
5.83	84.00	15.87	15.00	5.00	10.00
6.83	84.00	15.87	15.00	5.00	10.00
8.00	82.00	16.26	15.00	5.00	10.00
9.00	82.00	16.26	15.00	5.00	10.00
9.58	80.00	16.67	15.00	5.00	10.00
23.75	82.00	16.26	15.00	5.25	10.13
24.50	82.00	16.26	15.00	5.25	10.13
26.00	81.00	16.46	15.00	5.25	10.13
26.75	80.00	16.67	15.00	5.25	10.13
27.83	78.40	17.01	15.00	5.25	10.13
28.83	80.00	16.67	15.00	5.25	10.13
29.83	80.00	16.67	15.00	5.25	10.13
31.58	80.00	16.67	15.00	5.25	10.13
46.50	76.00	17.54	15.00	5.25	10.13
47.58	72.00	18.52	14.00	5.00	9.50
48.58	74.00	18.02	14.00	5.00	9.50
49.58	72.00	18.52	14.00	5.00	9.50
50.33	74.00	18.02	14.00	5.00	9.50
51.42	74.00	18.02	14.00	5.00	9.50
52.25	74.00	18.02	14.00	5.00	9.50

53.58	74.00	18.02	14.00	5.00	9.50
54.33	73.16	18.22	14.00	5.00	9.50
55.83	74.00	18.02	15.00	5.25	10.13
70.83	68.00	19.61	14.00	5.00	9.50
71.83	70.00	19.05	14.00	5.00	9.50
72.50	70.00	19.05	14.00	5.00	9.50
73.67	68.00	19.61	14.00	5.00	9.50
74.92	70.00	19.05	14.00	5.00	9.50

b) t CFV = 2.69 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	62.00	21.51	10.25	4.00	7.13
0.08	64.00	20.83	10.25	4.00	7.13
0.25	66.00	20.20	10.25	4.00	7.13
0.50	68.00	19.61	10.25	4.00	7.13
0.75	70.00	19.05	10.25	4.00	7.13
1.50	78.00	17.09	10.25	4.00	7.13
2.33	78.00	17.09	10.00	3.75	6.88
3.50	74.00	18.02	10.00	3.50	6.75
4.25	74.00	18.02	10.00	3.50	6.75
5.33	76.00	17.54	10.00	3.50	6.75
6.08	74.00	18.02	10.00	3.50	6.75
7.33	74.00	18.02	10.00	3.50	6.75
8.00	72.00	18.52	10.00	3.50	6.75
23.67	68.80	19.38	10.25	3.75	7.00
24.33	64.00	20.83	10.00	3.50	6.75
25.08	66.00	20.20	10.00	3.50	6.75
27.83	60.00	22.22	9.50	3.25	6.38
28.67	60.00	22.22	9.00	3.25	6.13
30.33	60.00	22.22	9.00	3.25	6.13
31.33	58.00	22.99	9.00	3.25	6.13
31.83	58.00	22.99	9.00	3.25	6.13
47.08	52.00	25.64	8.00	3.00	5.50
47.83	56.00	23.81	9.00	3.00	6.00
48.67	56.00	23.81	9.00	3.00	6.00
50.50	54.00	24.69	9.00	3.00	6.00
52.08	56.00	23.81	9.00	3.25	6.13
53.83	56.00	23.81	9.00	3.25	6.13
54.83	56.00	23.81	9.00	3.25	6.13
55.83	54.00	24.69	9.00	3.25	6.13
71.08	56.00	23.81	9.00	3.25	6.13

71.83	52.00	25.64	9.00	3.25	6.13
72.33	54.00	24.69	9.00	3.25	6.13
74.33	52.00	25.64	9.00	3.25	6.13

c) At CFV = 2.21 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	37.32	35.73	5.00	2.25	3.63
0.50	38.68	34.47	5.00	2.25	3.63
1.25	40.00	33.33	5.00	2.25	3.63
1.50	40.00	33.33	5.00	2.25	3.63
3.25	40.00	33.33	5.00	2.25	3.63
4.00	40.00	33.33	5.00	2.25	3.63
4.75	40.00	33.33	5.00	2.25	3.63
20.00	38.68	34.47	5.00	3.00	4.00
20.67	38.68	34.47	5.00	3.00	4.00
23.17	37.32	35.73	5.00	3.00	4.00
24.17	38.68	34.47	5.00	3.00	4.00
25.25	38.68	34.47	5.00	3.00	4.00
26.42	38.68	34.47	5.00	3.00	4.00
28.17	38.68	34.47	5.00	3.00	4.00
43.17	38.68	34.47	5.00	3.00	4.00
44.17	40.00	33.33	5.00	3.00	4.00
45.83	38.68	34.47	5.00	3.00	4.00
46.67	38.68	34.47	5.00	3.00	4.00
47.75	37.32	35.73	5.00	3.00	4.00
48.92	38.68	34.47	5.00	3.00	4.00
49.67	38.68	34.47	5.00	3.00	4.00
51.92	37.32	35.73	5.00	3.00	4.00
67.17	40.00	33.33	5.00	3.00	4.00
68.17	37.32	35.73	5.00	3.00	4.00

Table D2: COD removal performance data at different Crossflow Velocity (CFV) at MLSS 5000 mg/L

a) At CFV = 3.24 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading (gm/day)	Avg. Effluent Mass loading (gm/day)	Removal Efficiency %
0.00	96.00	28.63	41.91	2.75	93.44
0.92	96.00	28.63	41.91	2.75	93.44
3.17	96.00	28.63	41.91	2.75	93.44
3.83	96.00	28.63	41.91	2.75	93.44
4.42	96.00	28.63	41.91	2.75	93.44
6.00	96.00	28.63	41.91	2.75	93.44
23.92	88.00	30.31	42.76	2.67	93.76
26.17	88.00	30.31	42.76	2.67	93.76
28.17	88.00	30.31	42.76	2.67	93.76
46.83	80.00	32.50	43.85	2.60	94.07
48.92	80.00	32.50	43.85	2.60	94.07
50.67	80.00	32.50	43.85	2.60	94.07
52.58	80.00	32.50	43.85	2.60	94.07
53.92	80.00	32.50	43.85	2.60	94.07
56.17	80.00	32.50	43.85	2.60	94.07
72.17	88.00	27.00	41.10	2.38	94.22

b) At CFV = 2.69 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading gm/day	Avg. Effluent Mass loading gm/day	Removal Efficiency %
0.00	94.00	28.94	42.07	2.72	93.53
0.42	94.00	28.94	42.07	2.72	93.53
1.75	94.00	28.94	42.07	2.72	93.53
2.42	94.00	28.94	42.07	2.72	93.53
4.33	94.00	28.94	42.07	2.72	93.53
5.42	94.00	28.94	42.07	2.72	93.53
23.75	96.00	24.38	39.79	2.34	94.12
24.42	96.00	24.38	39.79	2.34	94.12
25.17	96.00	24.38	39.79	2.34	94.12
27.92	96.00	24.38	39.79	2.34	94.12
50.58	88.00	25.00	40.10	2.20	94.51
53.92	88.00	25.00	40.10	2.20	94.51
69.17	88.00	24.00	39.60	2.11	94.66
70.42	88.00	24.00	39.60	2.11	94.66

c) At CFV = 2.21 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading gm/day	Avg. Effluent Mass loading gm/day	Removal Efficiency %
0.00	96.00	15.38	35.29	1.48	95.81
3.50	96.00	15.38	35.29	1.48	95.81
4.25	96.00	15.38	35.29	1.48	95.81
19.50	104.00	19.38	37.29	2.02	94.59
23.67	104.00	19.38	37.29	2.02	94.59
27.67	104.00	19.38	37.29	2.02	94.59
42.67	104.00	16.56	35.88	1.72	95.20
43.67	104.00	16.56	35.88	1.72	95.20
51.42	104.00	16.56	35.88	1.72	95.20
66.67	112.00	13.90	34.55	1.56	95.49
67.67	112.00	13.90	34.55	1.56	95.49

Table D3: Hydraulic performance data at different Crossflow Velocity (CFV) at MLSS 3000 mg/L

a) At CFV = 3.39 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	82.00	16.26	15.00	5.75	10.38
0.67	82.00	16.26	15.00	5.75	10.38
1.17	84.00	15.87	15.00	5.50	10.25
2.00	88.00	15.15	15.00	5.50	10.25
2.50	90.00	14.81	15.00	5.50	10.25
3.25	88.00	15.15	15.00	5.50	10.25
4.00	88.00	15.15	15.00	5.50	10.25
7.00	88.00	15.15	15.00	5.50	10.25
7.50	88.00	15.15	15.00	5.50	10.25
20.83	86.00	15.50	15.00	5.50	10.25
21.67	86.00	15.50	15.00	5.50	10.25
23.00	84.00	15.87	15.00	5.50	10.25
24.00	84.00	15.87	15.00	5.50	10.25
26.50	86.00	15.50	15.00	5.50	10.25
27.50	86.00	15.50	15.00	5.50	10.25
28.50	86.00	15.50	15.00	5.50	10.25
29.50	82.00	16.26	15.00	5.25	10.13
45.50	82.00	16.26	15.00	5.25	10.13
46.33	82.00	16.26	14.50	5.25	9.88
46.92	82.00	16.26	15.00	5.25	10.13
49.50	84.00	15.87	15.00	5.25	10.13
50.33	84.00	15.87	15.00	5.25	10.13
52.50	82.00	16.26	15.00	5.25	10.13
53.50	82.00	16.26	15.00	5.25	10.13
68.50	84.00	15.87	15.00	5.50	10.25
69.50	82.00	16.26	15.00	5.50	10.25

b) At CFV = 2.76 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	76.00	17.54	10.00	3.75	6.88
0.17	74.00	18.02	10.00	3.50	6.75
0.50	74.00	18.02	10.00	3.50	6.75
0.83	76.00	17.54	10.00	3.50	6.75
1.83	74.00	18.02	10.00	3.50	6.75
2.92	74.00	18.02	10.00	3.50	6.75
18.17	70.00	19.05	10.00	3.50	6.75
19.33	68.00	19.61	10.00	3.50	6.75
21.58	70.00	19.05	10.00	3.50	6.75
25.33	68.00	19.61	10.00	3.50	6.75
26.08	68.00	19.61	10.00	3.50	6.75
26.83	66.00	20.20	10.00	3.50	6.75
42.08	66.00	20.20	10.00	3.50	6.75
42.92	66.00	20.20	10.00	3.50	6.75
43.83	64.00	20.83	10.00	3.50	6.75
45.08	66.00	20.20	10.00	3.50	6.75
47.08	55.12	24.19	10.00	3.50	6.75
48.00	56.88	23.44	10.00	3.50	6.75
49.08	66.00	20.20	10.00	3.50	6.75
50.92	64.00	20.83	10.00	3.50	6.75
66.33	66.00	20.20	10.00	3.50	6.75
66.92	64.00	20.83	10.00	3.50	6.75
67.83	62.00	21.51	10.00	3.50	6.75
69.83	62.00	21.51	10.00	3.50	6.75

c) At CFV = 2.25 m/s

Cumulative Time (hr)	Flux (l/m2/hr)	HRT (hr)	Inlet Pressure, Pi (psi)	Outlet Pressure, Po (psi)	Transmembrane Pressure, TMP (psi)
0.00	38.68	34.47	5.00	2.25	3.63
1.00	40.00	33.33	5.00	2.25	3.63
1.67	40.00	33.33	5.00	2.25	3.63
2.75	40.00	33.33	5.00	2.25	3.63
3.50	42.00	31.75	5.00	2.25	3.63
4.50	40.00	33.33	5.00	2.25	3.63
19.75	42.00	31.75	5.00	2.25	3.63
20.75	40.00	33.33	5.00	2.25	3.63
23.42	42.00	31.75	5.00	2.25	3.63
25.25	42.00	31.75	5.00	2.25	3.63
26.50	40.00	33.33	5.00	2.25	3.63
27.42	42.68	31.24	5.00	2.25	3.63
28.75	42.00	31.75	5.00	2.25	3.63
45.00	42.68	31.24	5.00	2.50	3.75
47.00	42.00	31.75	5.00	2.50	3.75
48.42	42.00	31.75	5.00	2.50	3.75
49.50	42.00	31.75	5.00	2.50	3.75
50.42	42.00	31.75	5.00	2.50	3.75
51.50	42.00	31.75	5.00	2.50	3.75
52.42	42.00	31.75	5.00	2.50	3.75
69.58	37.00	36.04	3.25	2.00	2.63
70.50	40.00	33.33	5.00	2.25	3.63
72.75	40.00	33.33	5.00	2.25	3.63
73.75	38.68	34.47	5.00	2.25	3.63
74.58	38.68	34.47	5.00	2.25	3.63

Table D4: COD removal performance data at different Crossflow Velocity (CFV) at MLSS 3000 mg/L

a) At CFV = 3.39 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading gm/day	Avg. Effluent Mass loading gm/day	Removal Efficiency %
0.00	88.00	30.31	42.76	2.67	93.76
0.67	88.00	30.31	42.76	2.67	93.76
1.17	88.00	30.31	42.76	2.67	93.76
2.50	88.00	30.31	42.76	2.67	93.76
20.83	88.00	30.00	42.60	2.64	93.80
27.50	88.00	30.00	42.60	2.64	93.80
46.92	88.00	30.94	43.07	2.72	93.68
68.50	80.00	30.24	42.72	2.42	94.33
69.50	80.00	30.24	42.72	2.42	94.33

b) At CFV = 2.76 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading gm/day	Avg. Effluent Mass loading gm/day	Removal Efficiency %
0.00	80.00	24.69	39.94	1.98	95.05
2.83	80.00	24.69	39.94	1.98	95.05
21.33	88.00	26.56	40.88	2.34	94.28
23.58	88.00	26.56	40.88	2.34	94.28
44.92	99.00	24.69	39.94	2.44	93.89
45.83	99.00	24.69	39.94	2.44	93.89
50.00	99.00	24.69	39.94	2.44	93.89
51.08	99.00	24.69	39.94	2.44	93.89
68.92	91.00	23.04	39.12	2.09	94.66
71.75	91.00	23.04	39.12	2.09	94.66

c) At CFV = 2.25 m/s

Cumulative Time (hr)	Effluent COD mg/L	Avg. Volume of Food (L)	Avg. Influent Mass loading gm/day	Avg. Effluent Mass loading gm/day	Removal Efficiency %
0.00	82.00	20.94	38.07	1.73	95.47
0.67	82.00	20.94	38.07	1.73	95.47
24.25	104.00	19.38	36.90	2.02	94.53
25.50	104.00	19.38	36.90	2.02	94.53
26.42	104.00	19.38	36.90	2.02	94.53
27.75	104.00	19.38	36.90	2.02	94.53
47.42	104.00	18.44	36.43	1.92	94.73
49.42	104.00	18.44	36.43	1.92	94.73
69.50	112.00	14.40	34.42	1.62	95.30
71.75	112.00	14.40	34.42	1.62	95.30
73.58	112.00	14.40	34.42	1.62	95.30

Table D5: variation of pH, SRT and MLSS before wasting during the experimental period

	At MLSS 5000 mg/L			At MLSS 3000 mg/L		
Day	MLSS	pH	SRT (Day)	MLSS	pH	SRT (Day)
1	5460		26.67	3537		8.00
2	5617	7.31	26.67	4814	6.79	8.00
3	5503		13.33	4100	6.51	3.33
4	5553		13.33	3837	6.94	10.00
5	5630	6.78	13.33	3837	6.94	10.00
6	5293	6.64	20.00	3790	7.08	6.67
7	5347	6.68	20.00	3370	6.85	40.00
8	5260	6.96	40.00	3363	6.85	40.00
9	5260	6.96	40.00	3363	6.85	40.00
10	4917	6.58	80.00	3284		26.67
11	5220	6.68	80.00	3733		26.67
12				3663	6.73	

APPENDIX E

RAW DATA FOR FOULING CONTROL

Table E1: Cleaning membrane with CLOROX

Cleaning time (min)	TMP (Psi)	Flux ($L/m^2/hr$)	Cleaning Agent
55	19.25	64.74	Clorox, pH=11.83
100	19.25	101.05	Clorox, pH=11.83
130	19.25	114.95	Clorox, pH=11.83
150	19.25	110.53	Clorox, pH=11.83
180	19.25	146.84	Clorox, pH=11.83
200	19.25	157.89	Clorox, pH=11.83
260	19.25	315.79	Clorox, pH=11.83
425	19.25	394.74	Clorox, pH=11.83
440	18.00	526.42	Clorox, pH=11.83
470	18.00	631.58	Clorox, pH=11.83
500	18.00	685.26	Clorox, pH=11.83
540	18.00	751.58	Clorox, pH=11.83
560	18.00	789.47	Clorox, pH=11.83
575	18.00	795.79	Clorox, pH=11.83

Table E2: Cleaning membrane with PERSIL and CLOROX

Run no. 1

Cleaning time (min)	TMP (Psi)	Flux ($L/m^2/hr$)	Cleaning Agent
60	15.75	189.47	Detergent (8g/L)
75	15.75	206.31	Clean water rinse
90	15.75	242.91	Clean water rinse
95	15.75	258.85	Clean water rinse
105	15.75	270.63	Clean water rinse
115	15.75	277.89	Clean water rinse
125	15.75	284.21	Clean water rinse
140	15.75	290.53	Clean water rinse
367	14.50	385.26	Clorox, pH=10.36
552	14.50	473.68	Clean water rinse
627	17.00	517.89	Clean water rinse
642	17.00	570.95	Clean water rinse

Run no. 2

Cleaning time (min)	TMP (Psi)	Flux ($L/m^2/hr$)	Cleaning Agent
75	18.50	121.33	Detergent (8 g/L)
100	15.50	157.89	Clean water rinse
120	15.50	181.58	Clean water rinse
135	15.50	180.00	Clean water rinse
145	15.50	189.47	Clean water rinse
150	15.50	189.47	Clorox, pH=10.27
165	15.50	221.05	Clorox, pH=10.27
180	15.50	252.63	Clorox, pH=10.27
200	15.50	271.58	Clorox, pH=10.27
220	15.50	274.74	Clean water rinse
235	15.50	274.74	Clorox, pH=10.27
265	15.50	394.74	Clorox, pH=10.27
280	15.50	394.74	Clorox, pH=10.27
295	15.50	418.42	Clorox, pH=10.27

Run no. 3

Cleaning time (min)	TMP (Psi)	Flux ($L/m^2/hr$)	Cleaning Agent
5	15.25	24.22	Clean water rinse
10	15.25	31.58	Clean water rinse
20	16.50	34.74	Clean water rinse
25	16.50	39.47	Clean water rinse
40	16.50	44.21	Clean water rinse
65	19.00	56.84	Detergent (8 g/L)
75	19.00	60.63	Detergent (8 g/L)
105	19.00	55.26	Detergent (8 g/L)
110	16.38	110.53	Clorox, pH=10.19
125	17.50	142.11	Clorox, pH=10.19
135	17.50	181.58	Clorox, pH=10.19
145	16.25	173.68	Clorox, pH=10.19
225	16.25	244.74	Clean water rinse
265	16.25	260.53	Clorox, pH=10.19
295	16.25	325.26	Clorox, pH=10.19
445	16.25	457.89	Clean water rinse

Table E3: Variation of Flux before and after cleaning

Cleaning with CLOROX and PERSIL				Cleaning with SUPERCLEAN			
Time (day)	Flux ($L/m^2/hr$)	Time (day)	Flux ($L/m^2/hr$)	Time (day)	Flux ($L/m^2/hr$)	Time (day)	Flux ($L/m^2/hr$)
0.0000	47.37	3.2951	71.59	0.0000	69.47	2.6146	140.00
0.1563	47.37	3.3160	71.59	0.0208	70.52	2.6528	138.00
0.1667	48.16	3.3993	71.59	0.0417	70.52	2.7083	136.00
0.2188	47.37	3.4514	72.63	0.0833	70.52	2.7708	134.00
0.2708	48.16	4.0972	73.67	0.1875	71.59	2.8333	134.00
0.9479	47.72	4.1250	74.21	0.2083	71.59	3.3889	138.00
1.0000	45.79	4.1597	74.84	0.2917	71.59	3.4722	134.00
1.0764	45.60	4.2326	72.63	0.3438	72.63	3.5313	136.00
1.1389	45.79	4.2882	72.63	0.9896	73.67	3.5972	132.00
1.1667	46.58	4.3264	72.63	1.0174	74.21	3.7257	90.00
1.3021	47.37	4.3715	73.67	1.0521	74.84	3.7396	86.00
1.9479	45.79	4.4514	73.67	1.1250	72.63	3.7500	84.00
2.0104	45.79	5.0972	68.43	1.1806	72.63	3.7604	80.00
2.0833	45.00	5.1215	67.36	1.2188	72.63	4.2847	73.32
2.1840	22.11	5.1389	67.36	1.2639	73.67	4.3160	76.00
2.2188	17.37	5.1597	67.36	1.3438	73.67	4.3403	77.32
2.2188	122.97	5.2326	66.32	1.9896	68.43	4.4201	81.32
2.2257	112.11	5.2847	65.27	2.0139	67.36	4.4583	81.32
2.2326	110.53	5.3125	66.32	2.0313	67.36	4.5625	81.32
2.2396	112.11			2.0521	67.36	4.6250	85.32
2.2500	113.68			2.1250	66.32	4.6979	82.68
2.2674	110.53			2.1771	65.27	5.2847	86.68
2.2778	110.53			2.2049	66.32		
2.2951	107.37			2.4271	66.32		
2.3160	104.21			2.9896	20.21		
2.3472	94.74			2.9896	126.00		
2.3681	91.58			2.4306	124.00		
2.3889	88.42			2.4340	122.00		
2.4201	85.26			2.4410	126.00		
2.4514	83.49			2.4479	128.00		
2.5451	74.21			2.4583	132.00		
3.1076	69.47			2.4688	136.00		
3.1285	70.52			2.4792	138.00		
3.1493	70.52			2.4896	140.00		
3.1910	70.52			2.5903	140.00		

APPENDIX F

RAW DATA FOR PERMEATE QUALITY PARAMETERS

Days	TOC (mg/l)	Days	Ammonia (mg/l)	Day	Permeate Plate count, CFU/ml	Tank plate count CFU/ml
4	16.08	6	21.23	5	1900	90000
9	12.15	9	17.31	60	11000	100000
12	14.17	12	13.56	96	6900	73000
13	20.10	13	10.93			
15	25.07	15	8.99			
18	11.48	18	7.6			
25	12.492	25	5.74			
27	31.343	27	10.6			
31	9.956	31	7.09			
34	10.4	34	3.46			
37	15.76	37	2.325			
41	14.533	41	3.024			
44	14.65	44	3.79			
46	16.093	53	0.96			
49	16.125	55	0.21			
51	15.25	68	53.4			
53	20.671	76	4.014			
55	28.027	80	7.75			
64	56.33	84	12.26			
66	16.322	87	8.83			
69	30.533					
77	14.92					

Days	Phenol mg/l	Days	Oil & Grease mg/l	Days	BOD mg/l
3	1.95400	4	1.1	2	1.2
11	0.86937	18	2.3	19	1
29	0.97738	29	1.9	29	0.8
30	0.84811	45	3.3	58	0.2
37	1.44057	52	1.1		
38	1.61771	56	3.5		
48	1.91095	70	1.5		
49	1.77451	81	1.6		
50	1.76014				
51	1.87402				
52	1.68115				
53	1.96122				
54	2.60467				
55	2.77510				
69	3.75296				
81	2.03303				
85	2.41005				
87	2.814				

VITA

OF

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- Bachelor of Science in Civil Engineering, 1999, Bangladesh University of Engineering & Technology (BUET), Dhaka, Bangladesh

PROFESSIONAL EXPERIENCE

- **Research Assistant**, King Fahd University of Petroleum & Minerals, Dhahran, KSA (November 01 to Present)

- **Civil Engineer**, Far East Corporation Ltd., Dhaka, Bangladesh (February 00 to October 01): To assist the Operation director for preparing project proposal, contract document and to select the subcontractors after the assessment of their performance. To support the consultant in foundation design and preparation of working drawing.

AFFILIATIONS

- Member of Institution of Engineers Bangladesh (IEB), Bangladesh.
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PUBLICATIONS

- ***Performance Study of Cross Flow Membrane Bioreactor (CF-MBR) in Treating Refinery wastewater***
  Author: Muhammad Muhitur Rahman and Dr. M.H. Al-Malack
  International Congress on Membranes and Membrane Processes (ICOM2005) conference to be held on August 21-26, 2005.

- ***Biochemical Kinetics of Cross Flow Membrane Bioreactor Processes in the treatment of Refinery wastewater***
  Author: Muhammad Muhitur Rahman and Dr. M.H. Al-Malack
  Manuscript under preparation